Measurement Techniques for Impulse Puncture Testing in Air

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Impulse voltage puncture testing (IPT) in air, as per IEC-61211, is used to assess the withstand strength of class B ceramic/glass insulators primarily against very fast front voltage transients (VFFTs) in power systems. This method uses short HV impulses of front times as low as 100ns, therefore, adequate execution and reproducible results are not ensured because no standard impulse shape exists for VFFTs, no calibration service exists for such systems below 0.84μs and the measurement system gets affected by many factors e.g. proximity effects, interferences, clearances and stray capacitances and inductances. This study focuses on investigating the testing practices and measurement techniques, for IPT in air as per IEC-61211, to find suitable testing methodologies.

Based on the results of a research survey done to know practices and capabilities of HV labs in this regard, testing was performed on a cap and pin insulator, mounted on a metal plate using ball-socket and stressed with steep front HV impulses. A 500mm wide copper sheet was used for grounding. Measurement system comprised of a fast resistive divider, a 50Ω tri-axial cable, a 10:1 attenuator of 50Ω input resistance and a 200MHz, 8bit, 2.5GS/s digitizer. The dependency of results on factors like divider-insulator distances, extra cable shielding, various target test voltages, HV damping resistor and different generation circuits was studied. No puncture of insulation happened.

The divider showed high overshoot in step response and low bandwidth in impulse results. Due to these reasons, along with its damage during testing, a new divider design is proposed for 500-600kV that is modular in structure and aims to solve the problem of low bandwidth by allowing its HV arm to be placed in direct contact with insulator. A novel algorithm is also proposed to analyse the linearity of front chopped impulses. It also revealed that following exact definition of T_c in IEC-60060-1 could result in it's wrong determination from measurement software.

Keywords: Impulse Voltage Puncture Testing in Air, Ceramic or Glass Insulators, Measurement Techniques of Very Fast Front HV Impulses, Chopped Impulses, Fast and Small Resistive Impulse Voltage Divider.

Preface

Praises to Almighty God for His gracious blessings, humble homage to the Holy Prophet Hazrat Muhammad P.B.U.H. and salutations to His Household A.S. and His Companions R.A. Lives of such great personalities have instilled compassion, hope, persistence, confidence, courage and many other qualities, that I didn't have, that helped me complete this thesis. I consider this work as the biggest struggle of my life, yet!

This work was not possible without the precious guidance of my supervisor Prof. Matti Lehtonen as he always gave me a lot of confidence and the independence to explore the work at hand. His time to time pointers guided me a lot. I also owe a lot to my advisor Mr. Jari Hällström (Research Team Leader, Electrical Metrology at MIKES, VTT Technical Research Centre of Finland Ltd.) and to Ma'am Marja-Leena from VTT; the way these two souls guided me is really commendable! What I learnt through discussions with these people was equal to reading many books. Then, I would like to thank Dr. Joni Klüss from Mississippi State University, USA for believing in me when he took me on board for this exciting and future changing project in terms of industrial practicality. His friendly attitude and humble personality always inspired me. Last, but not the least, I would like to thank Dr. Petri Hyvönen, Mr. Jouni Mäkinen and Mr. Niiranen Veli-Matti for helping me set-up my test benches throughout my thesis.

I would also like to acknowledge the funding for this research. This project has received funding from the EMPIR (European Metrology Programme for Innovation and Research) that is co-financed by the Participating States and from the European Union's Horizon 2020 Research and Innovation Programme. This joint project among multiple countries has really given me a flavour of rigorous research environment. I sincerely appreciate the support of all the relevant people and official organisations in this regard.

So, 2 years have gone by ever since I came to Finland. This was the best decision that I made in my life, which transformed me personally, academically and professionally. The aggregate of pain, joy, happiness, grief, suffering and, above all, struggle to not give up is what improved me at every level, day in and day out. I would like to dedicate this work to my parents, Syed Tanweer Hussain and Syeda Nasira, without whom I am no one! These two years were hard because of just one reason: I could not hug my mother and father whenever I needed. But I thank Skype and WhatsApp because they bridged the gap in testing times. The love, sacrifices, hard-work and patience with which my parents brought me up - I can never pay them back! Also, I would like to thank my siblings, Ahsan and Hina, for their love and support. My uncle Syed Tauqeer was the one who planted seeds of engineering in me, kudos to him! His tales on how he completed his master's thesis, with help of his wife Syeda Fakhra, really pushed me forward. I thank the support of my entire family as well.

I would further like to appreciate kindness and support of my ideals, friends, mentors and teachers, especially Nikola Tesla, Elon Musk, Mir Muhammad Alikhan, Wahaj Siraj, Abdullah Khan Niazi, Rabya Haider, Asim Aqeel, Bahzad Zaib, Syeda

Amber Zehra, Noman Nisar, Farhan Mahmood, Owais, Basri, Farid, Brozar Monaeb, Brozar Ahsan, Parsayan, Naveed bhai and all those whom I might have forgotten to mention.

Just like all those 100 year old manuscripts at Aalto University, if someone reads my thesis like 100 years ahead in future, know that everything will be al-right. Love yourself, stay happy, don't get stressed because you will eventually make it, be it any kind of struggle. But whatever you do, don't forget that your life is a blank book. Try writing a good story on it and you can't write a non-boring one without taking risks. Take risks because that's what will build you. If everything goes al-right, you will end up satisfied. If not, well, you will have stories for your grand children. Inspire people along your journey and be the light that illuminates darknesses. The world could use more humans like that!

I would end this preface by writing a poetic verse from Dr. Muhammad Iqbal, whose poetic works have been keeping the fire of passion alive for many years across canvas of many souls.

خدا تجھے کسی طوفاں سے آشنا کر دے

کہ تیرے بحر کی موجوں میں اضطراب نہیں

Translation: May you face a storm because your soul is devoid of passion.

I have seen some storms, may be not that harsh, but I hope more storms come that break me and then make me again!

Syed Husnain Tanweer Kazmi

Espoo, Aug 2016.

Contents

Symbols and abbreviations

0.1 Symbols

B	Bandwidth
C_B	Load capacitor
C_S	Impulse capacitor
d	distance/gap
f	frequency
L_{Du}	External series inductance
O_1	Virtual origin
R_D	Front resistor
R_{Din}	Internal front resistor
R_{Du}	External front resistor
R_E	Tail resistor
R_{Ein}	Internal tail resistor
R_{Eu}	External tail resistor
S	Steepness
T	Response time
T_a	Rise time
T_{alpha} / T_α	First partial response time
T_c	Time to chopping of impulse
T_p	Time to peak
T_1	Front time of impulse
T_2	Time to half of impulse
t_{max}	Maximum time (with respect to nominal epoch)
t_{min}	Minimum time (with respect to nominal epoch)
t_r	Rise time
t_s	Settling time
$U_{Ch,max}$	Maximum voltage of one stage of generator
U_{max}	Maximum voltage of generator
U_n	Nominal voltage of system
U_p	peak voltage
U_s	Highest voltage of system
U_{50}	50% disruptive discharge voltage of an object
W	Energy of impulse generator
Z	Characteristic impedance of cable
β	Percentage overshoot
ϕ	Diameter of one sphere in chopping/sphere gap

0.2 Abbreviations

AC	Alternating current
CAD	Computer aided design
CMC	Calibration and measurement capabilities
DC	Direct current
EHV	Extra high voltage
EMPIR	European metrology programme for innovation and research
EPR	Ethylene propylene rubber
EPDM	Ethylene propylene diene monomer
FFO/FFT	Fast front over-voltage / fast front transient
HV	High voltage
HV AC	High voltage alternating current
HV DC	High voltage direct current
IEC	International electro-technical commission
IOC	Instant of chopping
IPT	Impulse puncture testing
LI	lightning impulse
LV	Low voltage
MV	Medium Voltage
MVJ5000	Fast resistive divider of Aalto University's HV lab used in tests.
MVJ5000-N	Newly proposed or over-hauled design for the MVJ5000 divider.
NCI	Non ceramic insulator
NMI	National measurement institute
PD	Partial discharge
pu	Per unit
RC	Resistance capacitance (circuit)
RePe	Record of performance
RLC	Resistance inductance capacitance (circuit)
SFO	Slow front over-voltage
TOV	Temporary over-voltage
UHV	Ultra High Voltage
VFF	very fast front
VFFO/VFFT	Very fast front over-voltage / very fast front transient
WP	Work package

1 Introduction

1.1 Motivation

Electricity supply systems have passed through various evolutionary stages to reach the presently established form. Thomas Edison's first DC power transmission/distribution was so inefficient that most of the generation stations were built very close (with 2 miles) to the loads to keep line losses to the minimum. Nikola Tesla proposed HV AC transmission systems with the capability to transmit electrical power to very long distances with very low losses. In 1896 an 11kV AC transmission line was built between a power station at Niagara Falls and an industrial town Buffalo, 20 miles away from it in USA [25]. From that time onwards, the HV AC lines kept on developing more and more [36]. The ever increasing grid voltages, along with factors like over-voltage surges from lightning strokes, grid switching operations, environmental degradation etc. dictated better insulation to be used between different live and grounded parts in transmission lines. This sparked a huge interest in researchers and companies to study the effects of over-voltages from lightning strokes, one of the most crucial cause of insulation failure, using extensive testing [38].

Now-a-days UHV (Ultra High Voltage) grid voltages, as high as 800-1000kV AC in China for example, are being used in order to keep losses as low as possible [26]. Ceramic and glass insulators are used very extensively in these HV AC transmission lines along with an ever increasing use of NCIs (Non Ceramic Insulators) to provide the insulation. These insulators are exposed to the system voltage along with the very frequent over-voltages due to fast front and very fast front transients that originate in the power system due to faults, direct lightning stroke to conductor, back flash-over from grounded components, induced by stroke to a nearby object and disconnecter operations. The magnitudes of over-voltages could be from several hundreds of kilovolts to mega-volts, having time to peak less than 0.1μs and total duration of 3ms. The superimposed oscillations could have frequencies ranging 30kHz-100MHz [31] IEC-60071-1 [4]. If an insulator's dielectric strength or insulating property is strong enough then in event of such a transient, it may face a flash-over in air to the ground along it's surface instead of a puncture through the bulk of the insulation. Otherwise, the insulator could get punctured and result in outage of the line in case of one insulator. In case of a string of insulators, this puncture will decrease the overall insulating/withstand strength. The various kinds of over-voltages can be reproduced in lab using standardised voltage/impulse shapes as given in IEC-60071-1 [4]. However, no standard shape exists for very fast front transients (VFFTs).

Detailed testing is conducted on insulators, to assess their withstand strength to over-voltages that could result in puncture, prior to their installation to avoid such a scenario. The specific standard that deals with impulse puncture testing for Class B insulators (as per IEC-383-1 [9]) is IEC-61211 [1] and gives a detailed guideline regarding test requirements, insulator mounting arrangements, stress criteria, test voltage measurement, test procedure and acceptance criteria. However, such tests use short high voltage impulses with front times as low as 100ns and peak voltages as high as 500kV, therefore, their measurement is very difficult as compared to that of standard lightning impulses i.e. 1.2/50μs HV impulses [10]. The measurement circuit for such impulses is affected a lot by the proximity effects, spatial arrangement, mounting arrangements of the insulator, interferences, clearances to nearby grounded/live objects, inter-component distances, inter-connections, grounding, stray inductances and capacitances etc. Also, a large divergence exists between practices of various testing facilities due to usage of inappropriate equipment like LI dividers for measuring VFFTs. Furthermore, since no standard impulse shape exists for VFFTs, current NMI capabilities do not extend to front times below 0.84μs and no standard regulates the calibration of such measurement systems, therefore, the adequate execution of such tests and reproducible results of measurement of such fast impulses cannot be ensured.

This thesis is a part of Task 2.1 of WP2 (work package 2) of project ELPOW from EMPIR (European Metrology Programme for Innovation and Research). This project addresses all the above mentioned issues, along with many other from different fields, regarding very fast front impulse puncture tests in air and aims at improving the test procedures, measurement techniques, calibration methodologies and measurement capabilities by use of modern technologies, better dividers and faster systems. The main goal of Task 2.1 of WP2 of ELPOW is to design a small and fast resistive divider for properly measuring very fast front impulses with peaks up-to 500kV and rise times of below 200ns (front times below 250ns). Furthermore, new calibration methodologies for fast measurement systems, recommendations for a puncture testing methodology and a new input to revise IEC-61211 [1] are also goals of this project. More details and a public document regarding this project are available at [42].

1.2 Objectives of thesis

The objectives of this thesis are:

- To research the issues and problems faced by HV testing facilities in performing impulse puncture tests in air on glass/ceramic insulators. This will be done via an international research survey. The main objective here is to establish the state of the art by documenting the capabilities of the participating testing facilities regarding generation and measurement of very fast front HV impulses in impulse puncture tests in air.

- Using the results of the research survey, perform extensive testing to give recommendations on suitable puncture testing methodologies i.e. to evaluate how various factors in impulse puncture testing in air affect the results with special focus on measurement system and techniques. The already available fast resistive divider (MVJ5000) of HV lab at Aalto University will be used for this purpose.

- Using the results of various measurement techniques tested in previous point, propose a divider design that could help in developing a traceable infrastructure for very fast front impulse measurements, possibly for 500-600kV peak voltage and 200ns rise time (front times below 250ns).

– Recommend any other possible procedures or future work that could improve the state of the art regarding measurements in impulse puncture testing in air of ceramic/glass insulators.

1.3 Organization of thesis

The organisation of this thesis is given as below:

– **1 Introduction:** This gives the overview of the problem statement and the motivation behind it. It further chalks down the objectives that are aimed to be achieved at the end of this thesis.

– **2 Background:** This presents the required background knowledge that is necessary to understand the upcoming experimental work and results.

– **3 Research survey:** This presents the international research survey aimed at collecting and documenting the capabilities and practices of HV testing facilities regarding impulse puncture tests on ceramic/glass insulators in air.

– **4 Experimentation:** On basis of responses from survey and research done in background section, detailed testing was done on measurement techniques of VFFTs by keeping in view factors like inter-components distances, cable shielding, grounding, insulator mounting arrangements, various generation circuits etc.

– **5 Results and discussions:** Results and relevant discussions of the conducted testing are presented here.

– **6 Brief MVJ5000 characterization and design overhauling:** On basis of results from testing, a new divider design (MVJ5000-N) is proposed that is aimed at improving the results measured by MVJ5000. The design is also supposed to be modular, enabling it to be mass produced.

– **7 Conclusions and future work recommendations:** All conclusions drawn from experiments are presented here. Recommendations for any future work are also chalked down here.

2 Background

2.1 Over-Voltages and their standard impulse shapes

2.1.1 Basic terminologies

2.1.1.1 Nominal voltage of system U_n: The approximate voltage used to identify some system.

2.1.1.2 Highest voltage of system U_s: The r.m.s. value of highest phase to phase operating voltage which occurs under normal operations at any given instant and any given point in a system under observation.

2.1.1.3 Over-voltage: Any voltage:

- across one phase-earth or across some longitudinal insulation whose peak value is above peak of highest voltage in system divided by $\sqrt{3}$.
- across phase connections whose peak value is more than the amplitude of the highest system voltage.

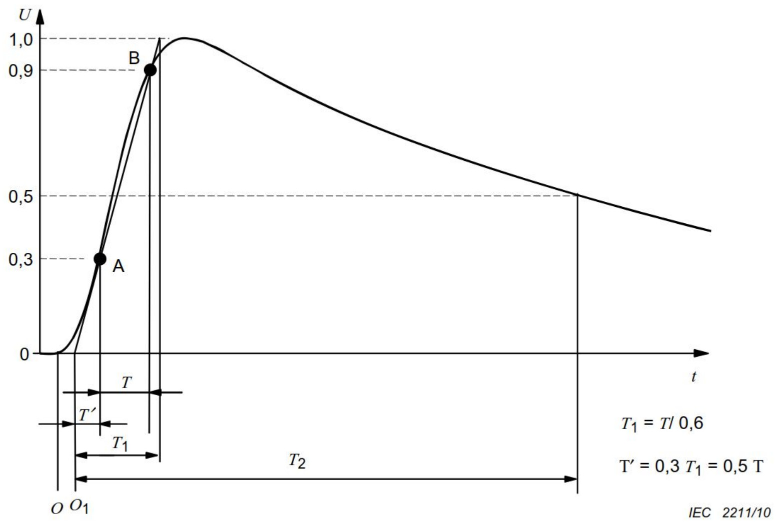


Figure 1: Full impulse voltage time parameters IEC-60060-1 [2].

2.1.1.4 Impulse voltage: An aperiodic transient voltage that is intentionally applied to a system. It rapidly rises to a peak and then falls gradually to zero.

2.1.1.5 Lightning impulse voltage: Impulse voltage having front time lower than 20μs.

2.1.1.6 Full lightning impulse voltage: Lightning impulse voltage which is not chopped.

2.1.1.7 Virtual origin O_1: A point preceding to A, as seen in Figure 1, on time axis by an amount of time $0.3T_1$.

2.1.1.8 Front time T_1: Its a virtual parameter defined as 1/0.6 times T (time between the points on time axis when impulse is at 30% and 90% of peak voltage value) as seen in Figure 1.

2.1.1.9 Time to half value T_2: A virtual parameter which is defined as the interval between O_1 and the instant when impulse has decreased to 50% of the peak/test voltage value.

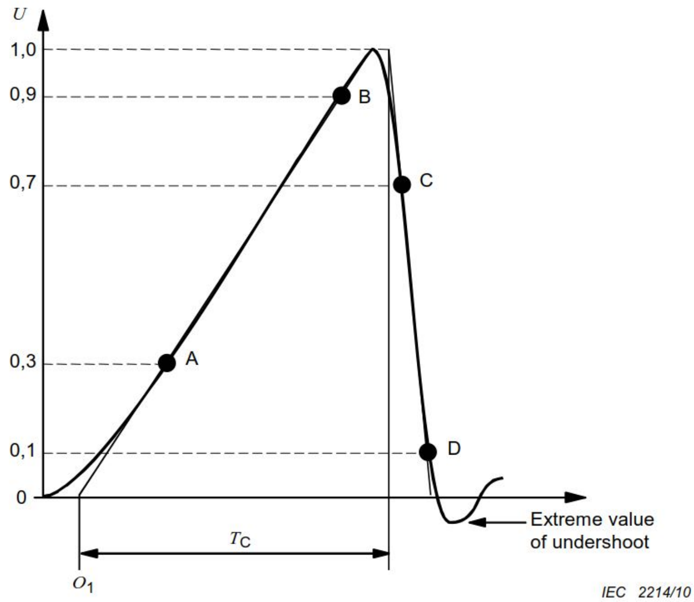


Figure 2: Lightning impulse voltage chopped on front IEC-60060-1 [2].

2.1.1.10 Chopped lightning impulse voltage: If a disruptive discharge interrupts a lightning impulse voltage so that the voltage collapses rapidly and practically to zero then the impulse will be termed as chopped lightning impulse voltage. It can be seen in Figure 2.

2.1.1.11 Instant of chopping (IOC): If a line is drawn through the 10% and 70% points on the voltage collapse part of impulse, then the point where this extrapolated line meets the voltage level immediately before the collapse, this point will be called instant of chopping. It can be seen in Figure 2.

2.1.1.12 Time to chopping T_c: Time interval between O_1 and IOC, as seen in Figure 2.

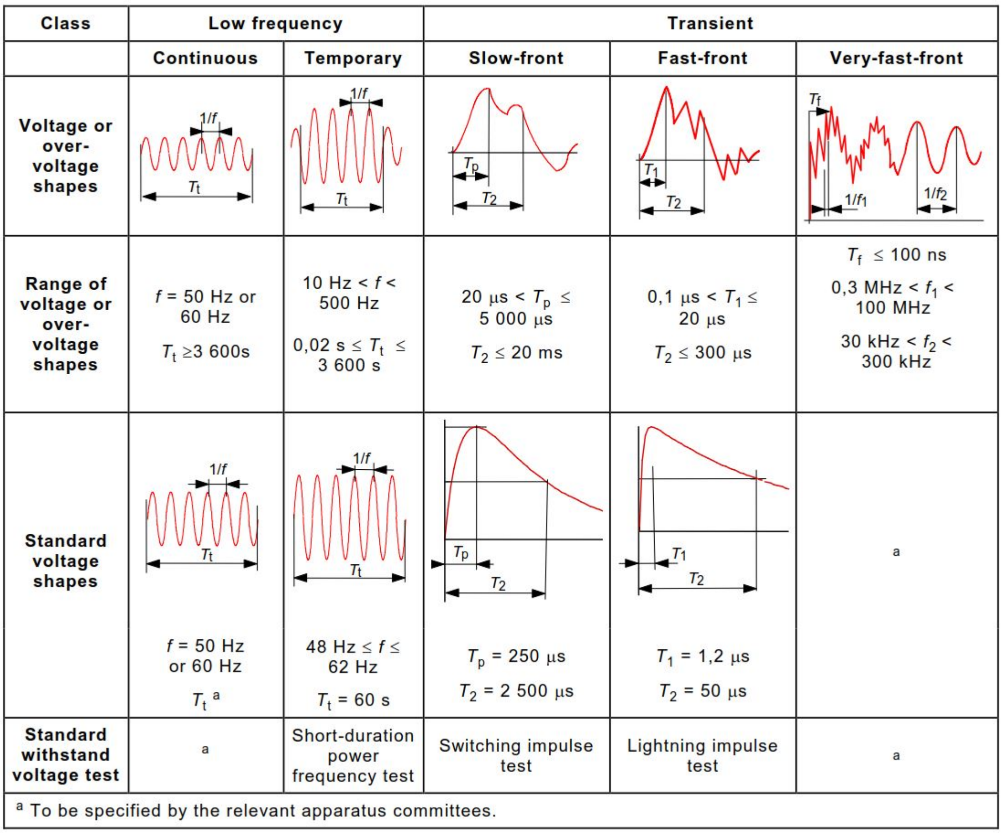
2.1.2 Voltage and over-voltage classifications

2.1.2.1 Continuous power frequency voltage: A voltage constantly applied between two terminals, having power frequency and constant r.m.s. value.

2.1.2.2 Temporary over-voltage TOV: A long duration power frequency over-voltage.

2.1.2.3 Transient over-voltage: An over-voltage whose duration is short i.e. milliseconds or less. It could be oscillatory or even non oscillatory and is normally highly damped.

2.1.3 Types of transient over-voltages



Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz T_t ≥3 600s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 μs < T_p ≤ 5 000 μs T_2 ≤ 20 ms	0,1 μs < T_1 ≤ 20 μs T_2 ≤ 300 μs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	f = 50 Hz or 60 Hz T_t [a]	48 Hz ≤ f ≤ 62 Hz T_t = 60 s	T_p = 250 μs T_2 = 2 500 μs	T_1 = 1,2 μs T_2 = 50 μs	[a]
Standard withstand voltage test	[a]	Short-duration power frequency test	Switching impulse test	Lightning impulse test	[a]

[a] To be specified by the relevant apparatus committees.

Figure 3: Detailed information about over-voltages as per IEC-60071-1 [4].

2.1.3.1 Slow front over-voltage SFO: A transient over-voltage which is normally uni-directional with time to peak $20\mu s<T_p\leq 5000\mu s$ and tail duration $T_2\leq 20ms$. Its also called as slow front transient (SFT).

2.1.3.2 Fast front over-voltage FFO: A transient over-voltage which is normally uni-directional with time to peak 0.1μs<T_1≤20μs and tail duration T_2<300μs. Its also called as fast front transient (FFT).

2.1.3.3 Very fast front over-voltage VFFO: A transient over-voltage which is normally uni-directional with time to peak T_f≤0.1μs and with or without superimposed oscillations at frequency 30kHz<f<100MHz. Its also called as very fast front transient (VFFT) or simply VFT.

Types of various over-voltages and their standard shapes are given in Figure 3. It must be noted that there is no standard impulse shape of very fast front transients/over voltages. This is one of the reasons that impulse puncture testing in air of glass/ceramic insulators and its practices see a lot of divergence in practices of measurement and equipment calibration.

2.1.4 Sources of some crucial over-voltages

Some sources of over-voltages as per [31] are:

2.1.4.1 Sources of temporary over-voltage: Earth fault, disconnection of load, resonance and ferro resonance and open phase or asymmetric connection.

2.1.4.2 Sources of slow front over-voltage: Connection of load to network, faults and re-closure, application of voltage and disconnecting load current.

2.1.4.3 Sources of fast front over-voltage: Direct lightning stroke to line conductor, back flash-over and induced by nearby lightning stroke.

2.1.4.4 Sources of very fast front over-voltage: Interruption of arc and re-striking or dis-connector operation.

2.2 Overhead Line Insulators

Electrical overhead power lines are distribution or transmission lines with or without shielding wires. High Voltage Transmission Lines are used to transport electrical power to far off regions because of lower amount of losses due to lower current in these lines. Distribution lines are used to distribute the same transmitted power to cities and industries by efficiently stepping it down to a lower voltage via grid stations. Overhead Line Insulators are used in such systems (along with grid station insulators) to ensure proper working of the system under all conditions.

Every power network utilizes insulators, be it at transmission level or distribution level. An insulator performs the following main functions in a power line [41]:

- To isolate/insulate the line from the grounded tower by acting as a non-conducting insulating support between live parts and by maintaining an air gap at working voltages.

- To resist electrical over-voltages.
- To maintain the mechanical strength of the transmission system by bearing the stresses resulting from conductor sag weight and weather conditions like snow etc.
- To perform all the above functions by fighting off environmental stresses like heat, ice, UV radiation, pollution etc.

Power system reliability is highly dependant on the quality and integrity of insulation system itself. If the insulation system fails at, say, national grid level then a large area could lose power for a long time. Similarly, insulation system failure could create complex problems where the power system will be pushed in state of instability and major generating stations would lose synchronism and trip out of the system.

2.2.1 Classification of Insulators

The classification of voltage systems is defined in IEC-60038 [8] as: Low Voltage Systems (up-to 1kV), Medium Voltage Systems (1kV - 35kV), High Voltage Systems (35kV - 230kV) and Extra High Voltage Systems (above 230kV). Ultra High Voltage is sometimes attributed by system voltages above 800kV. Each voltage level requires a corresponding level of insulation. Consequently, with increase in voltage their size also increases in terms of the distance between the line and the tower to avoid the flash-over of the insulators. The classification of overhead line insulators in IEC-383-1 [9] is:

- Pin Insulators
- Line Post Insulators
- String Insulators Units: Can and pin insulators and long rod insulators. String insulator units are combined together to form long strings.
- Insulators for overhead traction lines.

While this classification is pretty straightforward, insulators are further classified into classes according to the dimensions of the insulators in IEC-60383-1 [9]. They are:

- Class A: An insulator whose smallest puncture path within the solid insulation is atleast equal to half of the distance of arcing. The best example is the long rod insulator.
- Class B: An insulator whose smallest puncture path within the solid insulation is less than half of the distance of arcing. The best example is the cap and pin insulator.

2.2.2 Materials for Insulators

The materials of which these insulators are made of, as per IEC-383-1 [9], are:

- Ceramic material. The word ceramic material only refers to porcelain materials and doesn't refer to glass based insulators as done in North America.

- Toughened glass. Most mechanical stresses are controlled using thermal treatment of the material.

These days, apart from these two types, a new material type is also being used increasingly and is called the NCI (Non Ceramic Insulators). These are primarily composed of silicone rubber or EPR/EPDM rubber. The reason of using this material instead of glass/ceramics is the fact that NCIs have a lesser weight and higher tensile strength. NCIs also are easier to handle. The most important reason is the hydrophobic performance of the insulation, which is much better for NCIs and hence they can perform better in contaminated environments [22].

2.2.3 Example of a typical Cap and Pin Insulator

Cap and Pin Insulators are one of the Class B insulators. They are also known as ball and socket insulators or disc insulators. Various structural shapes are available for such them. A labelled diagram of a typical U120BL (IEC class of Insulators) cap and pin insulator is shown in Figure 4.

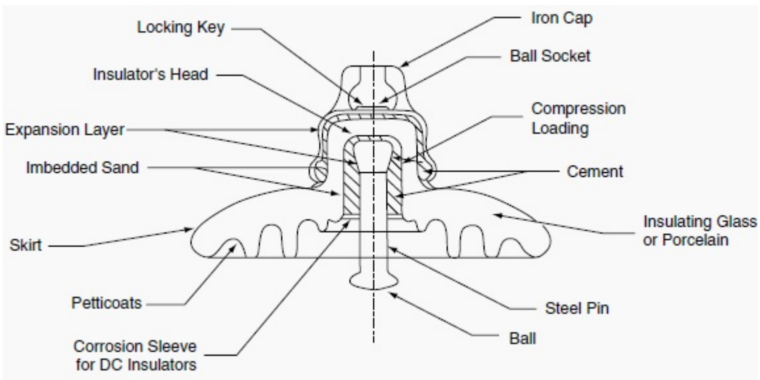


Figure 4: Parts of a typical disc or cap and pin insulator [29].

2.2.4 Stresses on external and internal insulation in ceramic or glass insulators

2.2.4.1 External insulation The external insulation is the one that is outside the bulk of insulation i.e. air and the surface of the insulator and is subjected to electrical stresses like full or partial flash-over of the insulation. With regard to the full flash-over, the power arc that is due to an earth fault also creates huge thermal and electrical stresses. These stresses deteriorate the insulation. Lines and insulators are designed while keeping these stresses in view.

2.2.4.2 Internal insulation The internal insulation is the bulk material of insulator from inside. The internal insulation is subjected to over-voltages and these over-voltages are limited via external insulation's flash-over. The insulator gets punctured if there is no external flash-over.

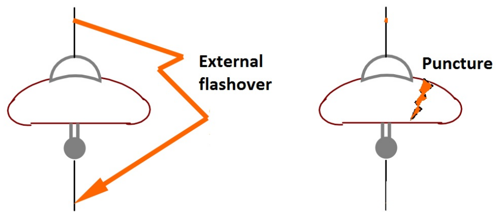


Figure 5: Flashover and puncture of an insulator unit [34].

2.3 Impulse Puncture Test (IPT) on insulators in air and it's need

Insulators in transmission lines are constantly faced with stresses that are caused by the system voltage, the low frequency over-voltages and the transient over-voltages, which have been discussed in detail in 2.1. For hassle free and reliable operation of transmission system, the deployed insulators must be able to withstand stresses appearing in all forms i.e. electrical, mechanical, thermal and environmental. In event of an over-voltage, the insulator may undergo a flash-over with the added compulsion that it should withstand that partial or full flash-over without getting damaged or punctured. Due to this reason, the transmission systems are designed with a tolerable risk of failure from the point of view of economics and safety. In this scenario, the type and the quality of the insulators play an important role. If an insulator's withstand strength is not enough towards over-voltages or the partial/full flash-overs, then it will possibly get punctured and will also short circuit the live and grounded parts via an ionised channel through the bulk insulation material. This could result in an outage in the transmission system if there is only one insulator between the line and the pole/tower. In case of a string of insulators, puncture of one or more units would lead to decrease in withstand strength of the overall insulation. This is the reason, individual units are replaced at regular intervals in strings of insulators of transmission lines [10].

Hence, to avoid such a scenario insulators are designed as per specific requirements. Many types of insulators were discussed in 2.2, each of which needs to be designed and manufactured by satisfying economic and quality pre-requisites. Different kinds of standardised tests are there to help in the designing, manufacturing and purchasing as well as to ensure good quality of insulators. Impulse Puncture Test (IPT) of insulators in air is among many of these standardised tests that ensures good quality of insulators. Class A insulators, as per IEC-383-1 [9], are not puncturable because of the long puncture path through the bulk insulation material. This test is actually meant for Class B glass and ceramic insulators (cap and pin insulators, long rod and pin and other similar types of insulators) which have a shorter path of puncture through the bulk insulation than the flash-over path in the air. NCI insulators have different definitions for such scenario, however this thesis deals with the ceramic and glass insulators only. IPT is conducted on ceramic and glass overhead line insulators in air, as per IEC-61211 [1], in order to ensure that they are capable to withstand stresses from fast front and very fast front over-voltages with a tolerable risk of breakdown/puncture. So if an insulator passes this test, chances are that it will not puncture when it faces high voltage transients and will result in an external flash-over in air over the insulator body. However, the insulator might be punctured by gradual stresses over time combined with a sudden over-voltage. The stresses may be thermal, electrical or mechanical along with simple ageing process. The main electrical stress is caused by VFFTs and lightning over voltages, and therefore, it should be simulated in lab via a test representative of service conditions. For the first time a proper guideline to conduct this test was conceived and finalised in a report called Type 2 IEC Report 1211 by Martti Aro in 1994 as a result of his years of research. This report later turned into an IEC standard i.e. IEC-61211 [1].

Any test should be representative of the actual service conditions that the relevant equipment will be exposed to. Furthermore, a test should be reproducible, repeatable and as well as selective. Prior to the advent of IPT in air as per IEC-61211 [1], the withstand strength of insulators towards the over-voltages was largely assessed using a power frequency test in oil as per IEC-383-1 [9] and insulator manufacturers also considered it good enough [17]. However, a comprehensive research done in [18] showed that this test is not reproducible, selective or even feasible. It also didn't represent service conditions. To tackle this impulse HV puncture testing on insulators in oil was studied [19] but that also didn't give any fruitful results and the results were also very confusing with no good interpretation [20], [21]. Compared to both, IPT in air is representative of service conditions to a huge extent due to the reason that an impulse voltage in air is itself representative of the stress conditions.

2.4 IPT in air as per IEC-61211 and elements of a typical IPT set-up

IEC-61211 [1] recommends puncture test as sample test. However, procedures for both sample and type test are given in it. The product standard defines the number of insulators to be used. If it doesn't then for type test the number is five while for sample test it is as in IEC-60383-1 i.e. puncture test. IEC-61211 [1] focuses on how to test ceramic or glass insulators by stressing them with steep front impulses. It defines some very basic mounting arrangements for various types of insulators, test requirements and procedure, compulsions on the specifications of the test equipment and acceptance criteria. Since in HV lab of Aalto university, only cap and insulators were available for experimentation, hence most discussion will be done as per that.

2.4.1 Mounting arrangements

The grounding conductor between the insulator and the divider should be a metallic sheet or plate. The cap and pin insulator must be put on an earthed plate with the cap side down. The plate's smallest dimension should be twice the diameter of the insulator. There should be enough distance between the plate the insulation bulk to avoid direct flash-over but it should be kept to minimum. The pin side of the insulator must be attached with a ball socket of same dimensions as the cap in order to ensure that the region doesn't get overstressed. The divider and the generator must be connected as in Figure 6.

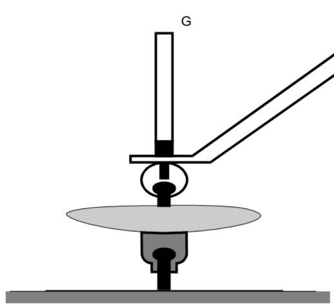


Figure 6: Mounting arrangements for cap and pin insulator. G is generator and D is divider IEC-61211 [1].

2.4.2 Impulse generation

For a single stage, the schematic for impulse generation circuit is shown in Figure 7. The capacitor C_s is charged and then discharged into other the C_B, R_D and R_E. This creates an impulse across C_B [11].

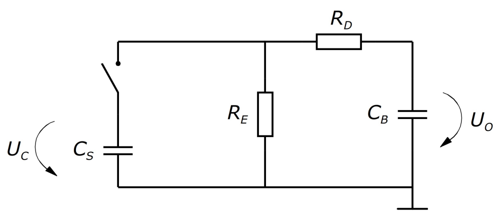


Figure 7: Single-stage impulse generator [11].

However, with higher charging voltages this single stage circuit doesn't remain feasible so the same circuit when improvised in multiple stages becomes Marx generator and can easily be used for very high voltages. The circuit is shown in Figure 8.

The capacitors C_s' get charged via the large valued resistors R_c'. Then the lowest spark gap is fired using a spark plug. This causes all the other spark gaps to fire.

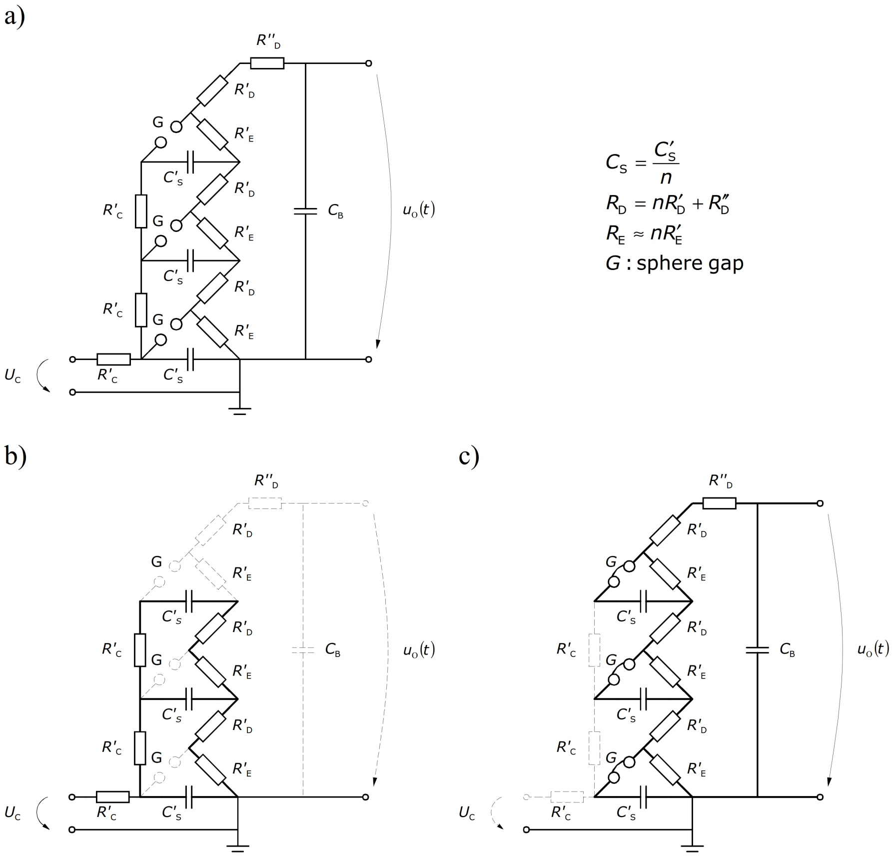


Figure 8: Multi-stage Marx generator. (a): One possible topology. (b): Active components during charging. (c): Active components during discharging [11].

Hence, all spark gaps get connected in series and in turn a HV LI is generated and discharged in the output network. Values of $R_D{}'$ and $R_E{}'$ control the front and tail time of the impulse [11]. For the generation of steep front impulses for the test, IEC-61211 [1] recommends that any LI impulse generator with open circuit voltage of 1000kV can be used if the impulse capacitance is not below a certain level. It further states that a generator with open circuit voltage of 500-600kV is usually enough in majority of the cases. If however difficulty arises in generation of high test voltages, a chopping or sphere gap in series with the test sample can be used. The series spark gap fires and a sudden voltage spike appears across the test sample which then gets chopped by the flash-over. This spike is actually a very fast front (VFF) HV impulse or simply steep front HV impulse [40]. So if a conceptual schematic is made for the circuit, it would be something like in Figure 9.

The Figure 9 shows a spark gap, a resistor and a capacitor as the steeping circuit parts, however a simple spark gap can also do the job as said by IEC-61211 [1].

A VFF HV impulse can also be created using an oscillatory LI generation circuit as shown in Figure 10. When the voltage is rising, it could be chopped by the spark gap and a similar spike like VFF HV impulse results as previously shown in potential diagram of Figure 9 [40].

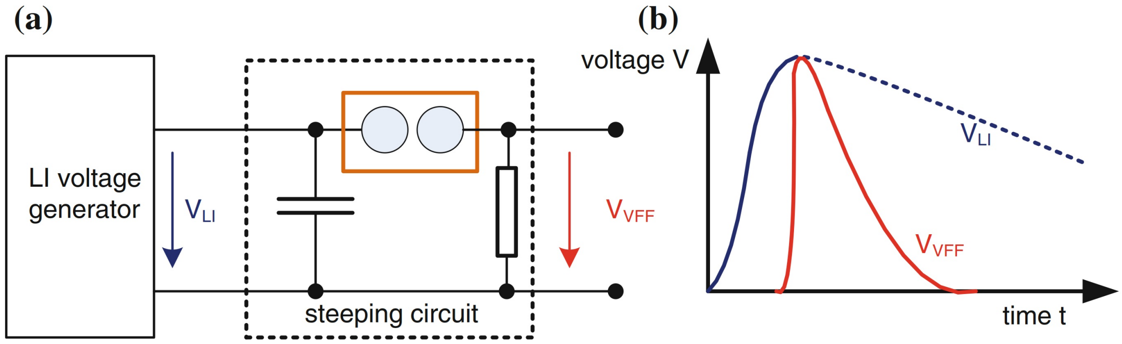


Figure 9: Steep front impulse generation. (a): circuit. (b): Potential diagram. [40].

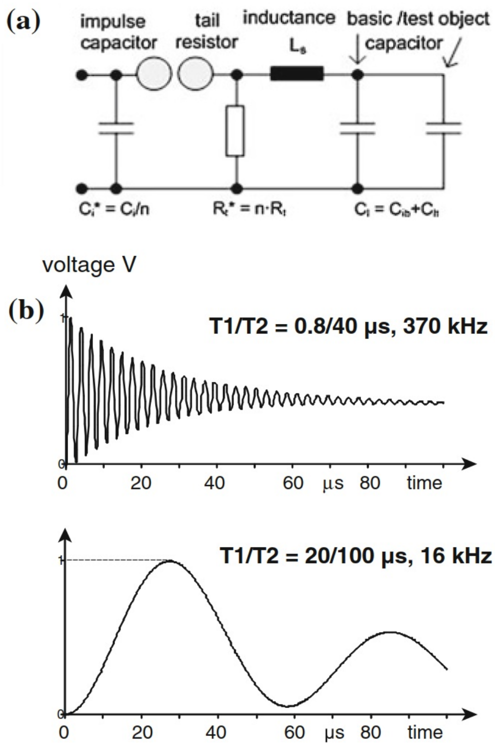


Figure 10: Steep front impulse generation using oscillatory LI generation circuit. (a): circuit. (b): Oscillatory LI HV impulse [40].

2.4.3 Test Voltage

The test voltage is the actual peak voltage found from the flash-over of the applied or incident steep front impulse voltage. Except the peak value, there is no requirement for the shape of the steep front impulse voltage. The duration of the steep front impulse is actually found out from it's flash-over. The circuit and/or charging voltage are varied until the flash-over of required peak value is attained. As far as the intended test voltage value is concerned, it should be specified by the product standard or its manufacturer or the agreement between manufacturer and purchaser. If that is not the case then it is some multiple of the U_{50} i.e. pu value with U_{50} as base. (U_{50}) is found out from a short standard string of cap and pin (3-5) units using Up-and-Down testing method as discussed in IEC-60060-1 [2]. For example for cap and pin insulators it is 2.8 pu. See Figure 11.

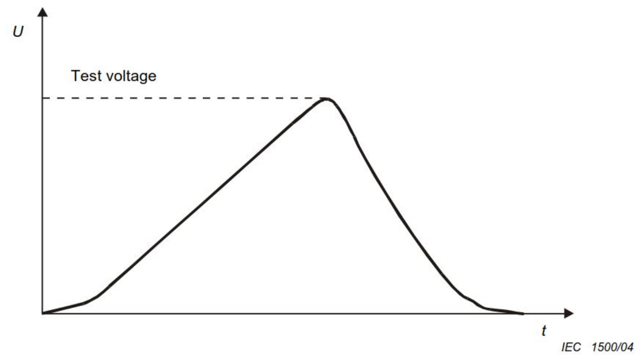


Figure 11: Applied steep front impulse chopped by flash-over of insulator at the test voltage IEC-61211 [1].

The pu values for the target test voltages have been prescribed in IEC-61211 [1] by keeping in view that they remain comparable to the previous requirement of 2500kV/μs when the stress criterion was steepness, and not the peak value. A graphical relation between pu test voltage value and U_{50} is given in Figure 12

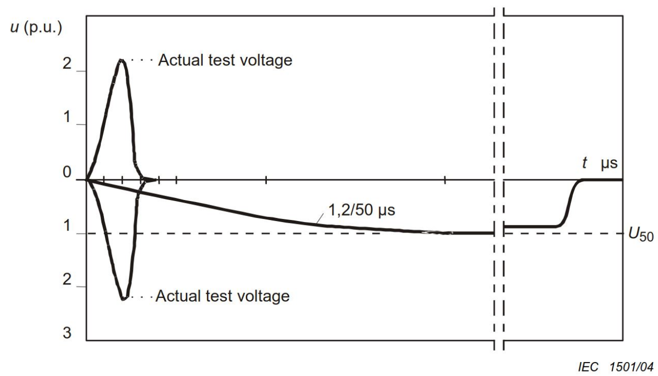


Figure 12: Relation between test voltage and U_{50} IEC-61211 [1].

2.4.4 Measuring system

A measuring system is a set of devices that are good enough to be used for an HV measurement IEC-60060-2 [3]. It normally includes:

- **Converting device**: A device that has the capability to convert the input quantity (voltage and the relevant time parameters) into a quantity which is in the input range of the measuring instrument (low current or voltage), yet maintains it's shape, time parameters and frequency components up-to a certain accuracy, hence giving the instrument a replica of the measurand. In most cases it is a simple voltage divider having an HV arm and a LV arm. The input voltage is applied to the HV arm while output is received from the LV arm. There are many other types of converting devices like voltage conversion impedance, transformer, electric field probe etc. The converting device or divider scales down the input quantity by a certain factor called the scale factor.

– **Transmission system**: A set of devices that transmits the output of the converting device to the measuring device/instrument's input. Mostly it is a simple co-axial or tri-axial cable along with its termination impedance. The cable is normally characterised by the surge impedance Z. Optional attenuators may also be present, which decrease the voltage to the input of the instrument even further. The presence of attenuators is taken into account for scale factor determination. For some applications optical type transmission systems are also used whereby a transmitter-receiver set with an optical cable is used.

– **Measuring instrument**: Device (a digital recorder or simply a digital scope these days instead of analogue peak voltmeters) that measures, displays and calculates any relevant parameters of the input voltage. After taking the voltage from the transmission system, the instrument then multiplies it with the pre-fed scale factor of the system. In most cases it has a native software for calculations, which is also a part of the measuring system as a whole. The software of the instrument calculates the parameters like impulse front time, time to chopping etc. as per standards.

The LV and HV arms of voltage dividers actually consist of several capacitors or resistors or both in various arrangements in series, resulting jointly in two main impedances, one of high value and one of low value. It must be noted that voltage dividers of various types are used for measurement of different kinds of high voltages, as shown in Figure 13. The measuring instrument is specially designed for impulse measurements [33].

A system with a purely resistive divider for HV LI is shown in Figure 14 to clear the concepts.

The Figure 14 however doesn't show the various system capacitances e.g. HV arm to ground and LV arm to ground, that are inherently present in every divider. Due to these capacitances, even a resistive divider performs like an RC circuit or a low pass filter. Along with these capacitances, stray inductances (lead inductances etc.) and stray capacitances (capacitance to nearby grounded metallic objects etc.) also add up to complicate the overall system one step further. Hence, every resistive divider, like any RC or RLC circuit, has properties related to its step response that define it's performance quality. They include parameters like rise time, bandwidth, response time, settling time and overshoot. However, the exact definitions for some of these parameters, in case of voltage dividers, are a little different than the standard

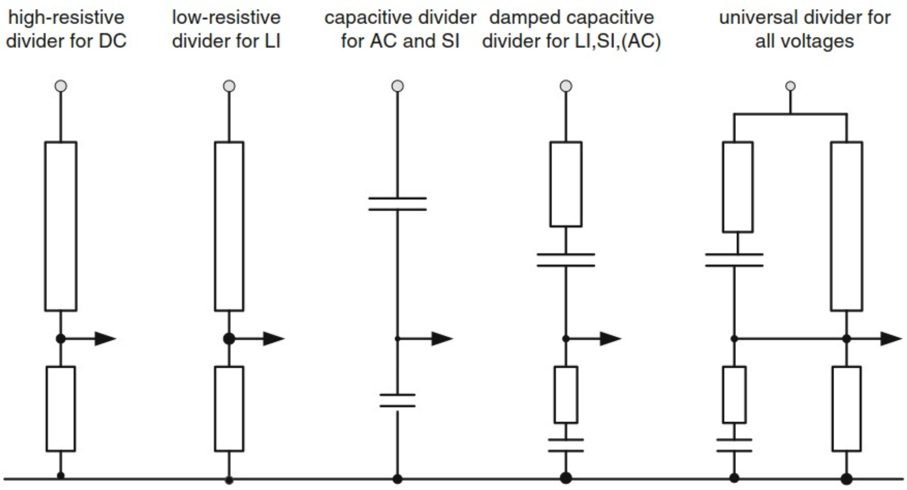


Figure 13: Different types of dividers for various kinds of high voltages [40].

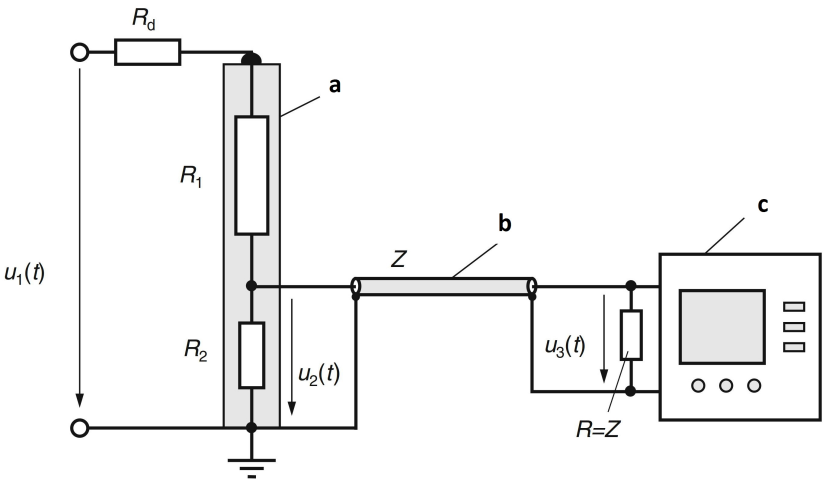


Figure 14: Impulse measurement system (a): Resistive divider. (b): Co-axial measuring cable with surge impedance Z. (c): Digital measuring instrument or oscilloscope. [39].

ones used in circuit theory. Those definitions of performance parameters of the measuring system as per step response and other the operating conditions are given in IEC-60060-2 [3].

Furthermore, every HV measurement system is characterised through it's assigned operating conditions under which the system operates within the uncertainty limits, they include i.e. assigned scale factor, rated operating voltage, the assigned measurement range(s) of the system, the assigned operating time and the number and/or kind of input quantity's (e.g. HV LI) assigned rate of applications and as well as the ambient environmental conditions. The digital oscilloscopes are usually characterised through their frequency response [39]. The assigned scale factor of a whole system includes the respective scale factors of everything in the system i.e. the divider, the cable, the attenuators and the instrument. The assigned scale factor should be calibrated so that he measurement is traceable to a standard. The calibration comprises of 2 main sections. The first is that the numerical scale factor must be computed by including the dynamic behaviour of the system. The second is that the uncertainty in whole measurement must be approximated or estimated with a suitable accuracy. When these conditions are met keeping in view the limits in IEC-60060-2 [3], the system becomes approved measuring system and is allowed to be used in accredited HV labs.

IEC-61211 [1] defines some performance specifications for measurement systems that are to be used in impulse voltage puncture tests of insulators in air. These specifications are given in order to gain the required uncertainty in the measurement. They are:

- The divider ratio must be known with an uncertainty of ≤2% (for k=2, k is the coverage factor).
- The overall uncertainty of the impulse measurement system must be ≤5%. (for k=2). Also, the system must be calibrated/approved as per guidelines in IEC-60060-2 [3].
- The measuring instrument or oscilloscope or digitiser must satisfy the conditions in IEC-61083-1 [6]. The rise time (0-100%) must be ≤12ns, while a minimum sampling rate of 500MS/s and resolution of 8bits should be used.
- Measuring system without instrument:
  - Oscillating response: First partial response time T_α must be ≤3ns.
  - Monotonic response: Response time T must be ≤5ns.

These conditions must be fulfilled with regard to the measurement system that is to be used for high voltage impulse puncture tests on ceramic/glass insulators in air. A recommended configuration for measurement circuit is given in IEC-61211 [1] as seen in Figure 15. However, this is a very vague representation since no parameter, like the distance between divider and insulator, is defined and simply this single factor could affect the results.

2.4.5 Procedural matters

There are some protocols/procedures that have to be observed during the test. They are described below:

- **Test procedure**: It is divided in two parts; one for cap and pin and class B long rod insulators while the other for pin insulators. The one for cap and pin is more relevant here and follows the pattern of impulses: 5 pos, 5 neg, 5 pos, 5 neg. A time gap of 1-2 minutes must be observed between impulses of similar polarity. In each impulse, peak value must be noted. If one impulse has peak voltage below and out of the tolerance then one supplementary impulse

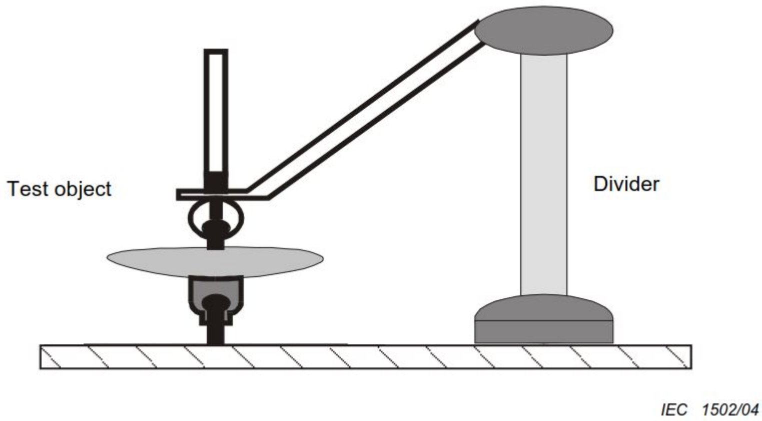


Figure 15: Configuration of divider and insulator sample [1].

must be fired. If it is above and out of the tolerance then the test must go on. However, if more than one impulse behaves like that then the test must be stopped and re-done on a new test sample after adjusting the whole test set-up.

– **Puncture determination**: In case of puncture not being visually visible, it can be determined by an absence of flash-over, or two consecutive flash-overs at standard LI or also at power frequency. The oscillogram can also be studied to determine the puncture.

– **Acceptance criteria**: Acceptance criteria are given in IEC-61211 [1] and can be consulted if needed, however they are not presented since it is not going to be applied in experimentation.

– **Re-test procedure**: If in sample test one unit fails then double the number of units are tested with same method. If any of these units fails, the lot doesn't comply with the standard.

2.5 Factors affecting results of IPT in air

In literature, many factors could be found that affect the outcomes of impulse voltage puncture tests on insulators. Those factors and how they are addressed by the IEC-61211 [1] and other supporting standards like IEC-60060-1 [2] and IEC-60060-2 [3], are summarised below:

2.5.1 Factors regarding steep front HV impulse generation

Many HV labs have stopped conducting impulse voltage puncture tests on insulators due to appearance of faults in the impulse generators, as described in [35]. The problems were in the form of the damages that the generators incurred when producing such steep front HV impulses. [28] has proposed a test kit for puncture tests, as shown in Figure 18, and is claimed to have reduced the damages of impulse generators. Using this kit [35] describes some studies on the puncture testing. For example, how a sphere gap could affect the results in the encapsulated and non-encapsulated forms as shown in Figure 16. Clearly, an encapsulated gap produces steep front impulses with less oscillations. Another point must be noted here that very limited literature clearly shows what a steep front HV impulse looks like, since there is no standard impulse shape for that matter. Increasing gap spacing and the gap-insulator distance adds oscillation in the impulse shape as shown in Figure 17.

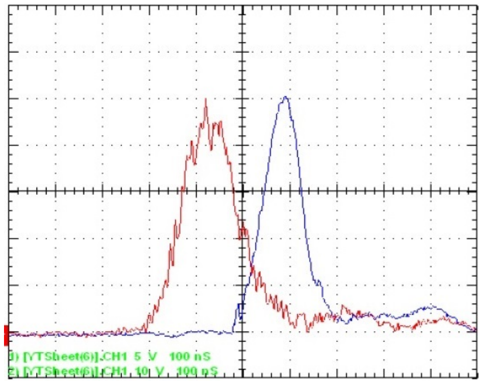


Figure 16: Results of using different sphere gaps. Red: result from non-encapsulated gap (gap:10cm). Blue: result from an encapsulated gap (gap:10cm) [35].

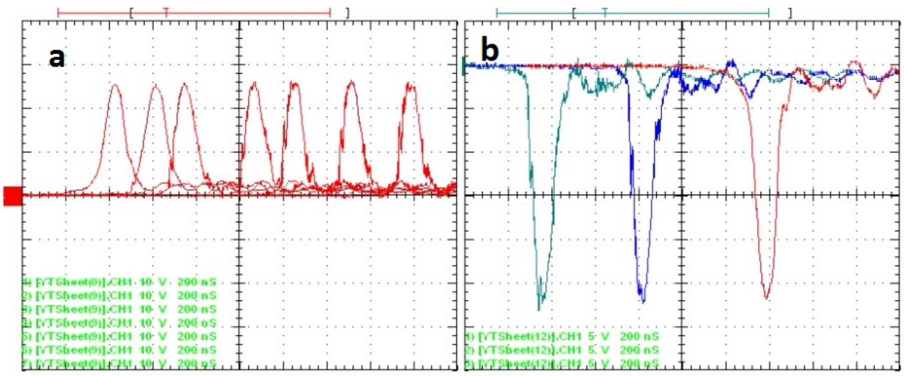


Figure 17: (a): Impulse shapes by varying gap spacing from 10cm to 70cm left to right. (b): Impulse shapes by varying connection between gap and insulator; green: copper sheet 30cm, blue: copper sheet 15cm, red: without a copper sheet. [35].

The stance of IEC-61211 [1] is very straight forward as already described in 2.4.2 i.e. it only describes very briefly about impulse generation circuit with very little and generic information. A puncture test kit [28] per se is a little difficult solution since it needs special fabrication. The impulse generation must be a simple procedure using off the shelf or readily available stuff in the lab, and be done in such a way so that there doesn't remain a need to use any kind of kit to solve impulse generation problems. This will be investigated in the upcoming experimentation. Also, there is no mention of oscillating LI generating circuits, in IEC-61211 [1] that could possible be used to generate steep front impulses for puncture tests. They will also be investigated in the experimentation. In a nut shell, the various mounting arrangements for the generation circuits will be tested and their effects on the measured results will also be studied.

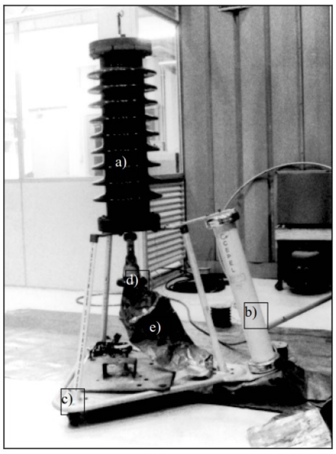


Figure 18: Puncture test kit [28]. (a): Compressed air insulated gap. (b): Resistive voltage divider. (c): Mechanical structure. (d): Insulation unit test sample. (d): Ground connection.

2.5.2 Factors related to measurement systems

The measurement system has been discussed in a reasonable detail in 2.4.4. All impulse dividers are expected to be fast (the extent of which depends on the impulse to be measured), have short settling time and have high withstand voltages. But impulse puncture tests employ short high voltage impulses (chopped by flash-over of insulator) with front times as low as 100ns, therefore, their measurement is very difficult as compared to that of standard lightning impulses i.e. 1.2/50μs HV impulses, and hence such voltages are usually measured with a relatively lower uncertainty [10]. But still it is not very easy to get good accuracies (or the overall uncertainty of 5%). The inter-laboratory comparison done in [14] shows that most labs had been measuring such short impulses with simple LI dividers of large sizes. Due to this errors are quite high and any attempt to correct the results by using steepness or response time is usually futile. Small sized and steep front impulse dividers are needed for such measurements because big ones get affected by stray inductances and capacitances [27]. For an RC circuit, the response time T of it's step response or T_a rise time decide how fast its response is i.e. the shorter, the faster. The equation 1 holds in this case. T_a is the rise time computed from step response i.e. time between the 10% and 90% of the peak of the step response.

$$T_a \approx 2.2RC = 2.2T \tag{1}$$

If 3ns is assumed as the value of T_{alpha} (equivalent to T of RC circuit) as the requirement for the measurement system without the instrument, described in 2.4.4, then as per equation 1 the T_a comes out to be 6.6ns. For simplicity, this value can just be assumed as 6ns. Using equation 2, the -3dB frequency or the bandwidth requirement for the system comes out to be approximately 60MHz.

$$Bandwidth = \frac{0.35}{T_a} \tag{2}$$

So, response time, rise time and RC time constant for a first order RC circuit can be related to each other for bandwidth requirement of the measurement system. A wedged shape impulse has been fired on an RLC circuit in Figure 19. T is the response time determined from step response of the circuit. With a value of T greater than zero, a peak value error is always there. When T is made to approach zero, the peak value error diminishes while oscillations get superimposed on the front and hence the determination of front time gets erroneous. The bandwidth lower than the required leads to large negative peak value errors, as calculated for non-oscillating response for an RC circuit above [39].

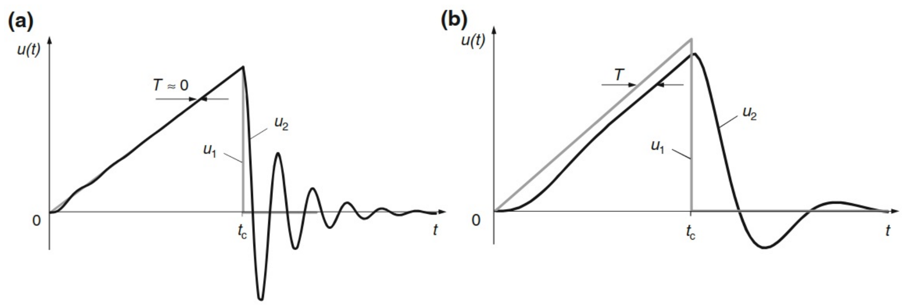


Figure 19: Effect of bandwidth (response time) on the measurement. u_1: input. u_2: output [39].

A few very good fast dividers are discussed in [15] and [16]. However, [10] has suggested that small resistive dividers made of several disc type ceramic resistors are very suitable for such measurements instead of large dividers or saline solution dividers (whose scale factor is dependant on the temperature). RC divider didn't really perform well as compared to resistive divider as could be seen in Figure 20.

The poor impedance matching of the measuring cable could introduce reflection phenomenon in the measured data. This could be avoided by adding impedance matching resistor network, whose input resistance is the same as that of surge impedance of measurement cable, at the instrument side of the cable. Similar network could be made at the divider side of the cable, with the possibility that it could be housed within the LV arm housing of the divider, as shown in Figure 21. The impedance matching resistor is also shown as R=Z in Figure 14.

The proximity of the divider to the nearby earthed or live objects could also affect the measurement results. While calibrating moveable dividers, clearances equivalent to those recommended for the test objected must be provided. The fixed dividers can be calibrated on site by neglecting the proximity effects [40]. In short, how properties

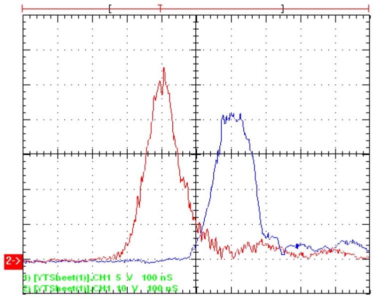


Figure 20: Comparison between impulses measured by different dividers. Blue: RC divider. Red: Fast resistive divider [35].

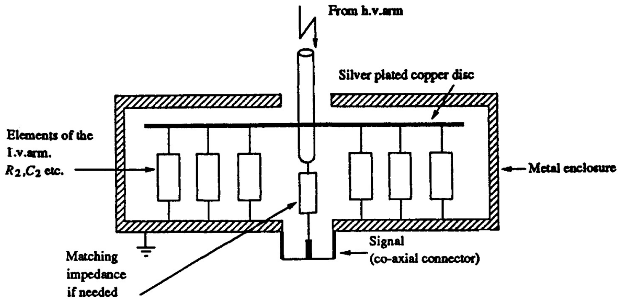


Figure 21: LV arm enclosure with impedance matching network [37].

like bandwidth and impulse shape are affected due to changes in the measurement circuit will be studied in the experimentation.

2.5.3 Factors related to interference

HV impulse measurements are generally prone to high level electromagnetic interferences. These interferences could be both conducted and radiated in nature. The prime causes are the interference currents in braids of the measurement cables induced by the nearby spark or chopping gaps in the impulse generation or the steeping circuit. If cable's own braid is not strong enough then these interferences get superimposed on the measured impulse [30]. A circuit is shown in Figure 22 which is designed to cancel out current interferences in the braid up to a large extent. The cable is routed through ferrite beads that force the disturbing signal to flow through the extra shielding, to the ground, which encloses this entire assembly. Hence, the braid of the cable itself becomes less prone to the interference currents. The skin effect also forces the interference currents to flow through the outer surface of the extra shield, hence saving the cable's braid from interferences one step further. The Figure 22 also shows, on the right, the systemic cancellation of superimposed oscillation on a current signal. In (a) there is a very noisy current signal, in (b) an additional braid has been used and in (c) the door of the system cabinet has been closed which nullified the capacitively coupled EMF and resulted in a noiseless signal.

This solution in Figure 22, however, needs specially sized ferrite beads. A simpler

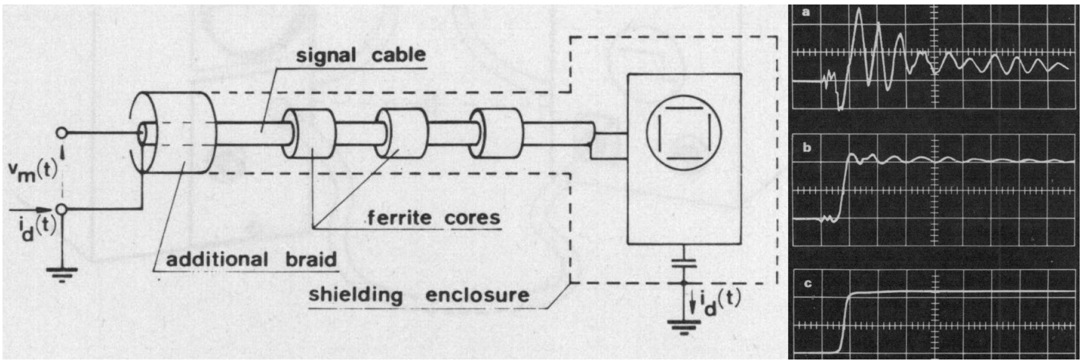


Figure 22: Left: an impulse measurement circuit for avoiding interferences. Right: cancellation of superimposed oscillation from top to bottom in a current signal. [30].

solution would be to use a tri-axial cable with two shields, although the punch through interferences of the braid increase with frequency. This could be made better by routing the cable through a metal corrugated pipe and then grounding that pipe. This pipe must be grounded with a common ground of the whole circuit so as to avoid earth loops and circulating currents. Also, the instrument should not be grounded directly, rather through the braid of the cable; this helps to avoid earth loops. The signal to noise ratio can also be improved by using high input voltages (as high as 2kV corresponding to maximum HV input voltage of the divider) to the instrument, but then an external attenuator might be needed as well. The instruments which are not protected against such effects must be placed in a shielded cabin (earthed) or Faraday cage and are fed power via isolating transformer located out of this cabin, also a power optimizer could be fitted to the external casing of the cage. This allows the induced interferences in the cage to be diverted to the ground without affecting the measurements. EM interferences also affect the divider since it acts as an antenna owing to the fact that only LV arm is shielded (in most cases) while HV arm is not. The firing of a nearby spark gap produces interferences that superimpose on the beginning part of the measured impulse and hence hinder the determination of 30% point on the front, and thus the front time. If the impulse is front chopped then the peak value determination can become erroneous [39].

2.5.4 Factors related to instrument and software

As recommended by IEC-61211 [1], the minimum sampling rate of the instrument must be 500MS/s with a resolution of 8bits. The instrument must have a rise time (0-100%) $\leq$12ns. Sampling rate smaller than this would result in less number of points in the sampled data for the same impulse, as compared to an instrument with a higher sampling rate and hence will result in loss of critical points on the impulse, resulting in peak and time parameter errors [39]. A high sampling rate should be accompanied with an increment in number of bits of native AD converter of the instrument for better performance. These days oscilloscopes have reached some very impressive limits in terms of sampling rates and speeds. The LabMaster 10-100Zi digital oscilloscope from TELEDYNE LECROY has a huge 100GHz bandwidth and a very high sampling capability of 240GS/s in real time. It has a rise time of 3.5ps (20-80%) and is therefore very fast [13]. Such instruments could be very beneficial to record steep impulses with a high accuracy provided the divider is fast enough with minimum errors.

These days digital oscilloscopes come with the capability to install commercial computer OS, like Windows from Microsoft, with an installable software for measurement from the manufacturer itself. A custom software could also be written for the recording and evaluation of impulse parameters. When an instrument is calibrated using an impulse calibrator, the functional verification of its software is also done for good enough evaluation of impulse parameters, as given in IEC-61083-1 [6], but it is only for some standard impulses of calibrator with smooth and noiseless waveforms and no provision is there for steep front impulses. The software must be able to recognise superimposed oscillations in order to correctly evaluate the parameters [39]. Apart from filtering the recorder data using the test voltage function k(f) there aren't many guidelines about the software. Instead of evaluating the efficiency of every individual software, the verification can be done using predefined data sets of some selected shapes of impulses. With this in mind an international comparison was made in [12] via non-variable data sets. Similar process in adopted in IEC-61083-2 [7] which shows so called Test Data Generator method as test specification via a designated software which can generate impulses of various forms, both experimental and analytically calculated data are included in it. The experimental data is generated using 3rd polynomials curve fitted to recorded data. However, all these methods somehow employ IEC-60060-1 [2] and IEC-60060-2 [3] for their functionalities and hence there isn't enough provision for steep front impulses. This further develops a need to do extensive research in this regard.

2.5.5 Factors related to test object

The capacitance of the sample insulator unit is normally low i.e. 10-100pF. The only main load on the circuit is a number of pre-discharges on the insulator surface due to the inhomogeneous electric field on the insulator's surface. These pre-discharges occur before the original flash-over itself and hence the current due to pre-discharges causes a drop of voltage whose magnitude depends on circuit impedance, voltage level, insulator's type and also the source capacitance. The result of these pre-discharges is that the impulse crest sees a rounding off effect [10].

2.6 Summary of areas to be investigated in experimentation

By looking at the discussions presented so far, it is quite obvious that a detailed study needs to be conducted on some very crucial areas regarding impulse HV puncture tests on glass/ceramic insulators in air. The focal point of the study should be the measurement circuit or technique since it's the most important part of the testing set-up. A summarised list of these areas is given as following:

- The effect of various steep front HV impulse generation techniques on the measured results.
- Mounting and grounding arrangements for the insulator.
- The effect of varying divider-insulator distance.
- The effect of extra cable shielding and cable positioning with respect to other components.
- The effect of any HV damping resistor connected to the HV arm of the divider.
- The effect of various combinations of all the above factors.

3 Research survey

3.1 Why is there a need to do it?

After going through the background knowledge in 2, the various technical issues present in IEC-61211 [1], the challenges in HV impulse puncture testing itself and the factors that affect the results of measurements, it was deemed important to know the capabilities and practises of high voltage labs and how they are dealing with mentioned technical challenges in a scenario where there is no calibration service for very fast front impulses at all. This need was felt because very little literature exists that shows even how a widely accepted steep front HV impulse looks like, let alone the generation and measurement methodologies, the equipment calibration practices, the physical mounting arrangements in the test circuit, cable shielding, the grounding methods and how all of these aspects collectively affect the measurement results in impulse voltage puncture tests of insulators in air. Websites of famous HV labs, insulator manufacturers and research centres of the US, the EU and many other countries were scanned but unfortunately very little relevant information was at disposal. Hence, it was decided that a research survey, in the form of a questionnaire, should be developed to know the current state-of-the-art of high voltage labs in impulse voltage puncture testing of insulators in air (as per IEC-61211 [1]) with respect to the various factors described above.

3.2 Method of execution

The objective was to make the survey as brief as possible without missing on crucial queries. Eleven questions were drafted and were sent to representatives of approximately 50 HV laboratories/research centres all across the EU, the USA and some other countries. The questions inquired about generation and measurement capabilities for very fast front HV impulses, calibration practices and uncertainty of equipment, mounting arrangements of the test sample, physical arrangement of test circuit, typical values for parameters like peak test voltage and the most common problems faced in impulse voltage puncture testing of insulators in air. It was also requested in the survey to send any documents, impulse records or even pictures of test set-ups that could provide the relevant help. The free on-line service of Google Forms was used to embed the questions on a web page and its web-link was emailed to all the potential participants.

3.3 Responses

Out of the 50 organisations, only 7 actually responded and recorded their experiences in the survey. 2 out of those 7 responders didn't perform impulse HV puncture tests on insulators in air, at all. The five entries that perform impulse puncture testing of insulators in air had quite a wide range of answers. The responses are listed on the next page.

Question	Answers				
	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5
1. Do you perform Impulse Voltage Puncture Testing (in air) of Ceramic/Glass Insulators by using IEC 61211?	Yes.	Yes.	Yes.	Yes.	Yes.
2. What other tests are you performing for ceramic/glass insulators?	Lightning impulse test, Power frequency test, Pollution test, DC tests, RIV test, Partial discharge test, Mechanical test.	IEC 60383, IEC 61109, IEC 62730 etc. See complete list accreditation L218 on internet RvA.	Dielectric test of IEC 60383-1.	RIV, LI, and PD.	Type tests according to IEC 60383-1, ANSI C29.2B etc.
3. Please describe the test setup briefly i.e. impulse generator circuit, mounting arrangements, measuring system etc.	Haefely 1200kV/60kJ impulse generator, Haefely resistive divider R500, Dr Strauss digital impulse voltage measuring system TR-AS 200-14, Lecroy LT364.	On request.	Impulse generator: 1400kV/35kJ, Spark-gap 250mm, Resistive divider 500kV. Digital oscilloscope 500MHz, 5GS/s, 10 kp.	Impulse generator of 1MV connected to encapsulated gap with external resistor. The insulator is mounted upside down below the gap. Resistive divider, attenuator, coaxial cable and oscilloscope.	Impulse generator, spark gap, insulator+divider. Mounting arrangement according to IEC 61211.
4. What are the typical peak voltage, steepness and rise time in these tests?	Peak voltage 400kV, Rise time 100ns.	Approx. 200 to 300kV, steepness > 1000kV/us up to 2500kV/us.	250kV, 1250kV/us, 200ns.	Peak voltage measurement with oscilloscope, 3000kV/us and rise time between 100ns and 200ns.	We test mostly glass cap and pin insulators. Peak voltage cca 300kV, steepness 2000-4000kV/us.
5. Do you use a spark/sphere gap in series with the test object?	Yes.	No.	Yes.	Yes.	Yes.
6. Do you use separate measurement systems for standard impulse testing and puncture testing?	Yes.	Yes	Yes.	Yes.	Yes.
7. Please, describe the complete measuring system(s) for puncture testing.	Haefely divider R500: partial response time < 10ns, Dr Strauss digital impulse system: sampling 200 MS/s 14bit, rise time 7ns, Lecroy LT364 oscilloscope: bandwidth 500MHz 8bit	NGK divider, digitizer HBM ISOBE 100MS/s.	Resistive divider 500kV, Ta= 3ns / Digital oscilloscope 500MHz, 5GS/s, 10 kp.	Fast resistive divider by Cepel, coaxial cable, attenuator, oscilloscope Tek type 7104 (8bit / 1GHz / 10GS/s).	500MHz oscilloscope+attenuator+small voltage divider.
8. What is the peak value measurement uncertainty of the measuring system for puncture testing?	Divider calibration < 1%, Dr Strauss uncertainty 1.5% for 0.5us front chopped wave, Lecroy LT364 oscilloscope 1.5%.	Good question, we have done research with Jari Hallstrom in 2012 and expect above 3%.	-	< 3% to peak.	Um cca 6%.
9. Does your laboratory have any accreditation for IEC 61211?	No.	No.	No.	No.	Yes.
10. Is your puncture testing measurement system calibrated? If yes, how?	Yes. Static calibration for divider and measuring system. Lightning impulse calibration with Kal 1000 system (Dr Strauss). Measurement of the divider response with unit step voltage generator (RIG 1000).	No, we only calibrate in full wave 1.2/50 us on lower value on system level. In 2012 Jari Hallstrom performed bandwidth measurement and step response measurements on component base. Report available on request.	Scale factor by DC voltage and dynamic response by step voltage.	Yes, it is calibrated with DC low voltage to SF and step response to measurement, Tn and T-alpha.	Yes, external company.
11. What were the main problems during setting up of generation and measurement systems for puncture testing?	Mainly interferences problems.	Difficult to find on the market good and reliable steep front measurement systems. Need enough bandwidth and sample time 1GS/s and remote fibre optic control. For stray capacitance we have special NGK divider. Please note that we also use divider for testing according IEC 60034-15 impulse testing on generator coils testing inter turn insulation.	Interferences. Mitigation is improved with oscilloscope into Faraday's cage.	Generation of wave form / steepness, measurement interferences and dynamic response of divider.	Generation of steep front impulses. Adding spar gap into system helped with generation of steep front impulses.

3.4 Results and their implications

Only one of the responders had a proper accreditation for testing with IEC-61211 [1]. The impulse generators ranged from 1200kV to 1MV (35kJ to 60kJ). One of them didn't use series spark gap for very fast front impulse generation. Almost all of them used fast resistive dividers with partial response time as low as 3ns and peak value measurement uncertainty of around 3%. 500MHz and 1GS/s digitising systems seemed to be quite common in use.

The most interesting point was that most of them mentioned interference as a big problem faced during impulse puncture tests. Other notable problems were issues in generation of the very fast front HV impulses, poor dynamic response of the divider and stray capacitances/inductances. For testing procedures, most of them followed those given in IEC-61211 [1], but no specific information about clearances, inter-component distances, cable shielding or system grounding was provided.

These observations from the survey, along with the presented background knowledge and the fact that very few labs are working in this field, confirmed the hypothesis that there was a need to do extensive research on procedures of impulse voltage puncture testing on insulators in air. The entire paradigm revolves around the measurement system. In that respect, a focused research was needed that must define appropriate methods of generation of steep front impulses and their measurement techniques. Along with that the effects of system grounding, cable shielding to prevent interferences, distances between various equipment, physical ways to interconnect everything with metal foils/pipes, various spark gaps and insulator mounting methods were needed to be investigated.

4 Experimentation

The experimentation was carried out along the same lines as concluded in the research survey but the testing here was not done strictly in accordance with IEC 61211 [1]. Instead of the actual testing, the purpose of these tests was to find out information for next revision of IEC 61211. Main target was to test practical and optimal solutions for the test set-up with respect to proper generation and measurement methods of very fast front HV impulses, mounting arrangements of insulator, test circuit grounding, cable shielding etc.

4.1 Equipment for testing

All the testing was carried out in the small HV hall of Aalto University. It's actually a Faraday cage and the floor has a grounding mesh below it with grounding nut-bolt assembly after every few square meters, where equipment could be grounded. The following equipment was used for making the test set-ups:

4.1.1 Steep front impulse voltage divider, transmission system and attenuator

The fastest divider available in Aalto's HV laboratory is a small sized resistive divider (MVJ5000), specially designed for very fast front impulses or steep front impulses. The HV arm consists of 26 ceramic disc resistors connected in series, each of 200Ω. LV arm is a single disc type 10Ω resistor of same dimensions. In Figure 23, R1 represents the HV arm while R2 is the LV arm. R3 is the impedance matching network and consists of two 80Ω colour coded carbon resistors in parallel, amounting to 40Ω. T1 is Belden-9888, 50 ohm tri-axial measuring cable. R4 and R5 collectively form a fast resistive attenuator (10:1), having 50Ω input resistance. The detailed specifications of attenuator are in [23]. The entire system has an assigned scale factor of 10260. The details of construction of an older version of the same divider are given in [10].

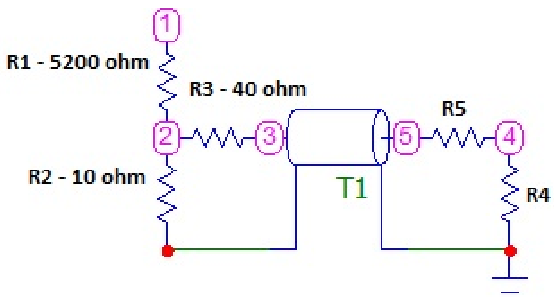


Figure 23: Schematic for MVJ5000.

The HV resistors were stacked one above the other by using an acrylic rod, pushed through the central hole of each disc resistor. The whole HV arm is enclosed in an acrylic tube, on top of which rested the HV toroidal electrode. This entire HV arm structure is mounted on to an aluminium plate (800mm in diameter and 4mm in thickness) which is supported by four non-metallic insulating legs. The total height of the divider from the floor was 831mm with 700mm flash-over distance. The aluminium plate has a 250mm long and 100mm wide copper strip attached to it that allows proper grounding. The LV arm is just below the aluminium plate but axially under the HV arm. The LV arm is housed in a closed and hollow metallic cylinder (70mm in length, 75mm in outer diameter and 69mm in inner diameter). The aluminium plate, the LV arm housing and the copper strip are all equipotential bodies. See Figure 24 for pictures of MVJ5000.

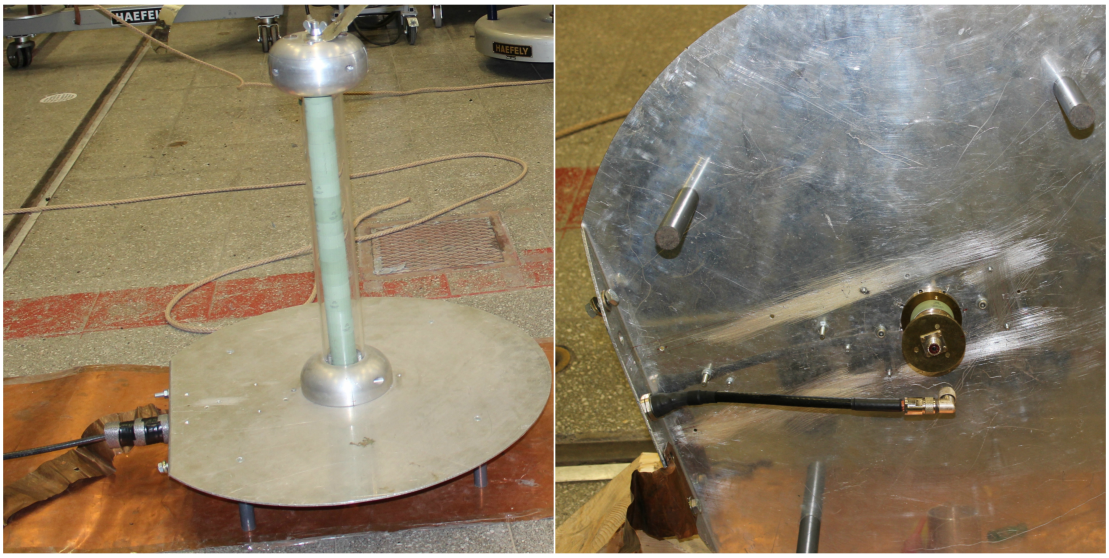


Figure 24: MVJ5000. LV arm is visible under the aluminium bottom plate.

4.1.2 Transient recorder

A 4-channel, 200MHz, 8bit oscilloscope/digitizer with capability of sampling at 2.5GS/s (LeCroy WaveSurfer 24Xs) was used for recording the impulse voltages. The maximum allowed input voltage was 80V. It also supports Microsoft Windows OS as the native software that could run various other software. The software used for steep front impulse measurement was VEEpro_LeCroy_29attn_select_mvj_steep.vee. This software was indigenously developed at Aalto University and works by getting installed in the transient recorder itself. The oscilloscope has a calculated 10-90% rise time of 1.75ns. The IEC-61211 [1] required the oscilloscope to have a 0-100% rise time of less than 12 ns in order to be used in impulse puncture testing. Hence, the oscilloscope satisfied the requirement of IEC-61211 [1].

4.2 Determination of U_{50} voltage of test sample

The test sample in experiments was a glass cap and pin type insulator unit U120BL. It was an old one which suffered numerous flash-overs, so it's surface was full of traces. Prior to making the various test set-ups and assessing them, test voltage values by which the sample insulator unit should be stressed, must be known. The test voltage is some multiple of the average lightning impulse 50% flash-over voltage (U_{50}), found out from a short standard string of cap and pin units using Up-and-Down testing method as discussed in IEC-60060-1 [2]. 3 insulator units were mounted in the string. The test voltage was measured by G600 divider and its software. The impulse was the standard lightning impulse i.e. 1.2/50μs. The overall uncertainty of the measuring system was $\leq$2%. The circuit shown in Figure 25 and Figure 26 was employed for determining the U_{50} voltage of the test sample. R_{Din} and R_{Du} are the internal and external front resistors, respectively. Similarly, R_{Ein} and R_{Eu} are the internal and external tail resistors, respectively.

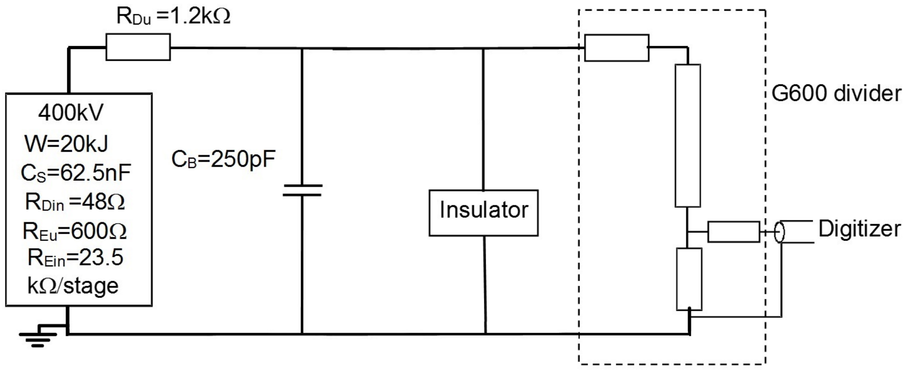


Figure 25: Circuit for determination of U_{50} voltage of U120BL cap and pin insulator unit.

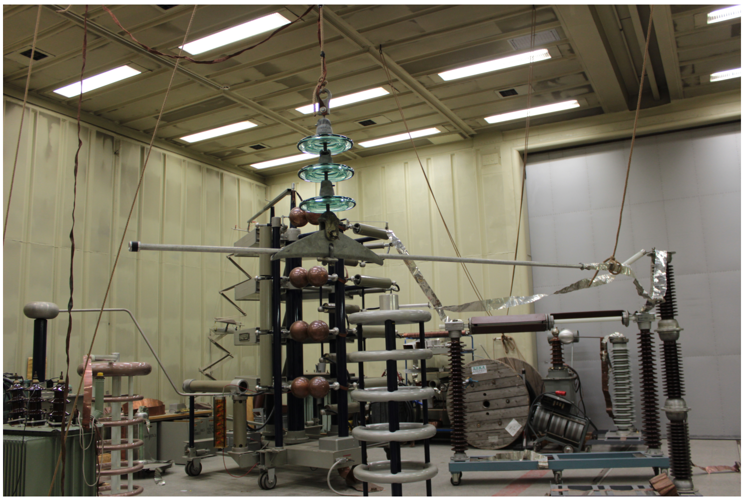


Figure 26: Physical test set-up for determination of U_{50} of U120BL cap and pin insulator unit.

14 positive impulses were used and the voltage variation for each impulse was 5kV. The U_{50} came out to be 98.9kV.

4.3 Preliminary information about testing of various measurement techniques

All of the tests were conducted in air. Since the test sample is a cap and pin insulator, the test voltage should be 2.8pu of the average lightning impulse 50% flash-over voltage (U_{50}). This requirement is only when the test voltage is not specified by the product standard of some specific cap and pin insulator or its manufacturer or the agreement between manufacturer and purchaser. Hence it was decided to stress the insulator with target of a wide array of test voltages. The Table 1 shows the various target test voltages keeping in view U_{50}=98.9kV. IEC-61211 [1] further gives the tolerance for the test voltage as 0 to +10%. The observed test voltage should be within this range for every impulse fired.

pu value	Test voltage absolute value (kV)	Tolerance range by IEC 61211 (kV)
2.3	227	227 - 250
2.8	277	277 - 305
3.2	316	316 - 348

Table 1: Various target test voltages and their tolerances values

At least two target test voltage levels were tested for the test sample in each case. So if it is written in future something along the lines, for example, Circuit A1 2.8pu pos case then it means that for circuit A1 charging voltage or steepness has been adjusted to achieve test voltage peak in tolerance range of 2.8pu with positive polarity as per IEC-61211 [1]. Also, it goes without saying that impulses can (and will sometimes) deviate from these tolerances. The test sequence was fixed for all test set-ups. 10 positive and 10 negative pulses were applied, with the interval of more than 1 minute, at any given test voltage level. The target in every impulse set was to achieve a certain test voltage from flash-over of the insulator. Not all of these voltages levels were targeted for every test circuit. Prior to actual impulses in every impulse set, some trial impulses were fired to adjust the charging voltage and steepness in such a way so as to achieve the targeted stress level. But of-course, peak test voltage could vary during the actual test impulses and they were recorded as such. Although ambient conditions were noted down, but they were not applied in terms of corrections. The reason for this is the fact that IEC 61211 [1] recommends it as such.

4.4 Steep front HV impulse generation circuits

Two methods were used for generation of steep front HV impulses for stressing test sample in various measurement circuits.

4.4.1 With series sphere/chopping gap

This had a double-loop impulse generating circuit. The first loop was a slightly modified form of an LI generator while the second loop was switched on by using a sphere gap having spheres of diameter of either 250mm or 500mm and the air gap between spheres was 100mm or 100mm/117mm, respectively. The simple schematic for this case is shown in Figure 27. The following impulse generator setting was used:

- Haefely 800kV: 4 stages, U_{max} = 800kV, $U_{Ch,max}$ = 200kV.
  C_S = 62.5nF, W = 20kJ.
  R_{Eu} = 600Ω, R_{Ein} = 23.5kΩ/stage.
  R_{Din} = 48Ω, R_{Du} = 600Ω, C_B = 250pF.

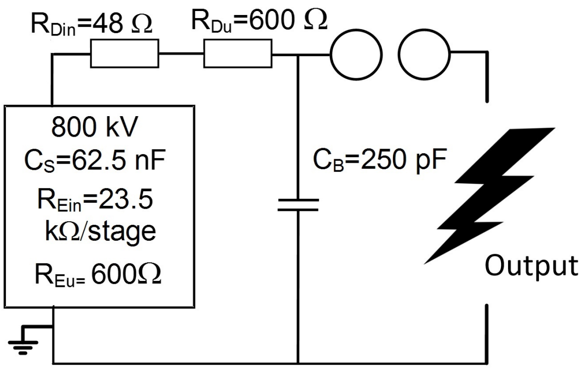


Figure 27: Schematic for generation circuit with series chopping/spark gap.

4.4.2 Oscillating circuit (without series spark/chopping gap)

Compared to the impulse generation circuit with series chopping/spark gap, this one doesn't employ any series spark gaps after the load capacitor. The only spark gaps in the whole system were in the impulse generator. Also, no front resistor assembly was present in these circuits and was replaced by a 10μH series inductor. The schematic for this case is shown in Figure 28. The following impulse generator setting was used:

- Haefely 800kV: 4 stages, U_{max} = 800kV, $U_{Ch,max}$ = 200kV.
  C_S = 62.5nF, W = 20kJ.
  R_{Eu} = 600Ω, R_{Ein} = 23.5kΩ/stage.
  R_{Din} = 36Ω, R_{Du} = 0Ω, C_B = 250pF, L_{Du} = 10μH.

The impulse generator shown in Figure 8 gives an idea on how various resistances and capacitances were connected in the generation circuits.

4.5 Steep front HV impulse measurement circuits/techniques

In all measurement circuits or techniques, the basic objective was the same i.e. to record the test voltage and complete steep front impulse. Physically it was done by connecting the divider's HV arm to the top part of insulator where the steep front

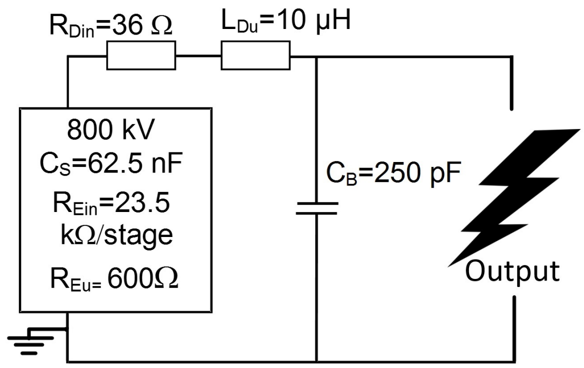


Figure 28: Schematic for generation circuit without series chopping/spark gap.

HV impulse stroked and flashed over the body of the insulator (with the possibility of puncture, of-course). This could be achieved using various possible physical arrangements of the components of the circuit. Some arrangements will remain the same, however, which are described here. The insulator was mounted onto a earthed/grounded aluminium plate (diameter 330mm and thickness 10mm) via a pin (diameter 16mm and length 100mm) with the cap side down. This plate was then put on a long grounded copper sheet (500mm wide, 1mm thick) which spanned from the load capacitor to the other end of the divider i.e. all the measurement circuit components were placed on it. Furthermore, this copper sheet and load capacitor of the impulse generator were grounded/bolted to the lab's common earthed mesh under the floor, at the same point. The ball socket on the cap side of the insulator was fixed while another similar detachable ball socket was added to the pin side of the insulator. A meshed copper type material was inserted between the pin and the ball sockets (on both sides of insulator) to make good electrical contact. The divider was also put on and grounded to the 500mm copper sheet through a copper foil connected to its bottom plate. The measurement cable was connected to the MVJ5000 divider and was routed through the wall of the shielded control room. At the other end, in the control room, the cable was connected to the 10.0:1 SJT 1744 attenuator which in turn was connected to the LeCroy WaveSurfer 24Xs digitizer/oscilloscope. This digitizer was further placed on a table, while there was another piece of the similar grounded copper sheet between the table and the digitizer. The attenuator and the cable were grounded to this copper sheet with a clamp and a piece of a small copper foil. All other inter-connections, as per schematics, were made using 100mm wide aluminium foil. Maximum efforts were made to avoid group loop currents by keeping grounding points to minimum.

4.5.1 Type A techniques

These measurement techniques were tested by stressing the insulator with steep front HV impulses generated by the series sphere gap type generation circuit with $\phi =$ 250mm (sphere diameter) and d = 100mm (gap spacing).

Circuit	Construction
A1	Divider-insulator mid-mid distance of 1300mm, both connected with 100mm wide aluminium foil. The foil was held in place by a rope. No extra cable shielding or HV damping resistor (for HV arm of divider) was present. Angle between 100mm wide foil and cable was 180 degrees. Cable, attenuator and instrument grounded in the instrument end.
A2	Same as A1, with the difference that the measuring cable was provided with extra shielding in form of a corrugated metal pipe, of inner diameter 30mm, having no connection with the cable (at it's end connectors), it was just covering it. The extra shielding was grounded to the 500mm wide bottom grounded copper sheet using a clamp, and wasn't further grounded near the instrument in order to break the path of interference currents.

4.5.2 Type B techniques

These measurement techniques were tested by stressing the insulator with steep front HV impulses generated by the series sphere gap type generation circuit with $\phi =$ 500mm and d = 100mm or 117mm.

Circuit	Construction
B1	Divider-insulator mid-mid distance of 1300mm, both were connected with 100mm wide aluminium foil which was held in place by a rope. The foil was rather more straight/flat as compared to the one in A1. Angle between 100mm wide foil and measuring cable was 90 degrees. No extra cable shielding or HV damping resistor (for HV arm of divider) was present. Cable, attenuator and instrument grounded in the instrument end. The bottom 500mm wide grounded copper sheet consisted of two parts, joined by a clamp.
B2	Divider-insulator mid-mid distance of 1550mm. The divider was turned so that the angle between 100mm wide foil and cable became 180 degrees. Rest was same as B1.
B3	Same as B2 but the measuring cable was provided with extra cable shielding. The extra shielding wasn't connected to the cable (at it's end connectors) and was just covering it. It was grounded to the bottom 500mm wide grounded copper sheet using a clamp, and wasn't further grounded near the instrument in order to break the path of interference currents.

4.5.3 Type C techniques

These measurement techniques were tested by stressing the insulator with steep front HV impulses generated by oscillating type generation circuit (without series spark/chopping gap).

Circuit	Construction
C1	Divider-insulator mid-mid distance of 1800mm, both were connected using 100mm wide aluminium foil. Distance of divider to removed sphere gap (used in B type measurement circuits) was 1800mm while to the lab door it was 2600mm. The measuring cable was provided with extra shielding which was not connected to the cable (at it's end connectors) and was just covering it. The extra shield was grounded to the bottom 500mm wide grounded copper sheet using a clamp. No HV damping resistor was used at the HV arm of the divider. The bottom 500mm wide grounded copper sheet consisted of two parts. Cable, attenuator and instrument grounded in the instrument end.
C2	A 75Ω damping resistor was added in between the divider and the insulator which changed the scale factor to 10425. The damping resistor was suspended in air with help of rope tied to the roof of the lab. At both ends of the resistor, 100mm wide aluminium foil pieces were used to make connections to divider and the insulator. Everything else was same as C1.
C3	Same as C2 with the difference that the distance between divider and insulator was reduced to 1000mm in order to achieve a shorter loop.
C4	This was like C1 i.e. having no 75Ω damping resistor between the divider and the insulator. C4, however, had divider-insulator mid-mid distance of 1000mm as compared to 1800mm in C1. Everything else was exactly like C1 including the scale factor of the measurement system (scale factor: 10260).

4.6 Pictures and schematics

In this subsection the schematics along with photographs of the measurement circuits are shown. The purpose of showing both is to maintain clarity while doing discussions on results in the next section.

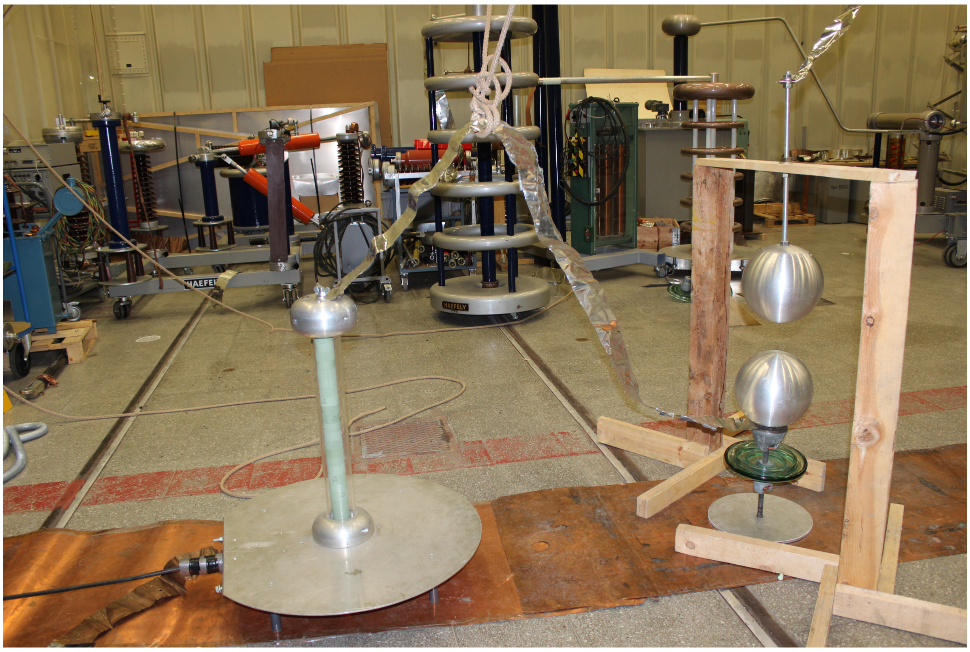


Figure 29: Measurement circuit A1.

Figure 30: Measurement circuit B1.

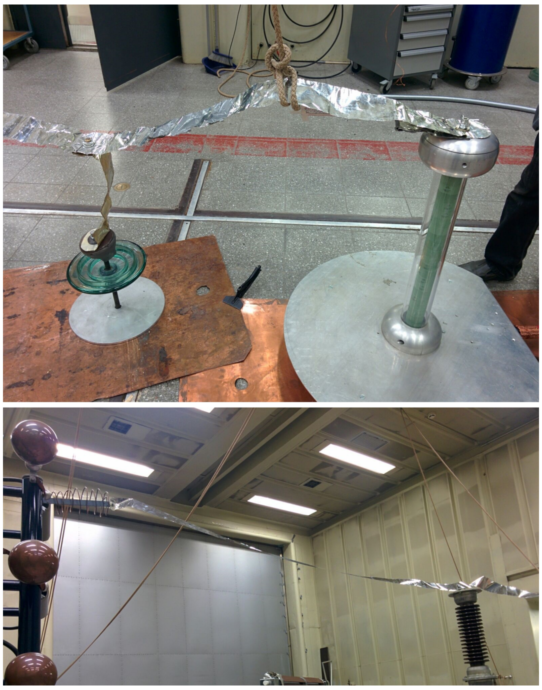


Figure 31: Measurement circuit C1.

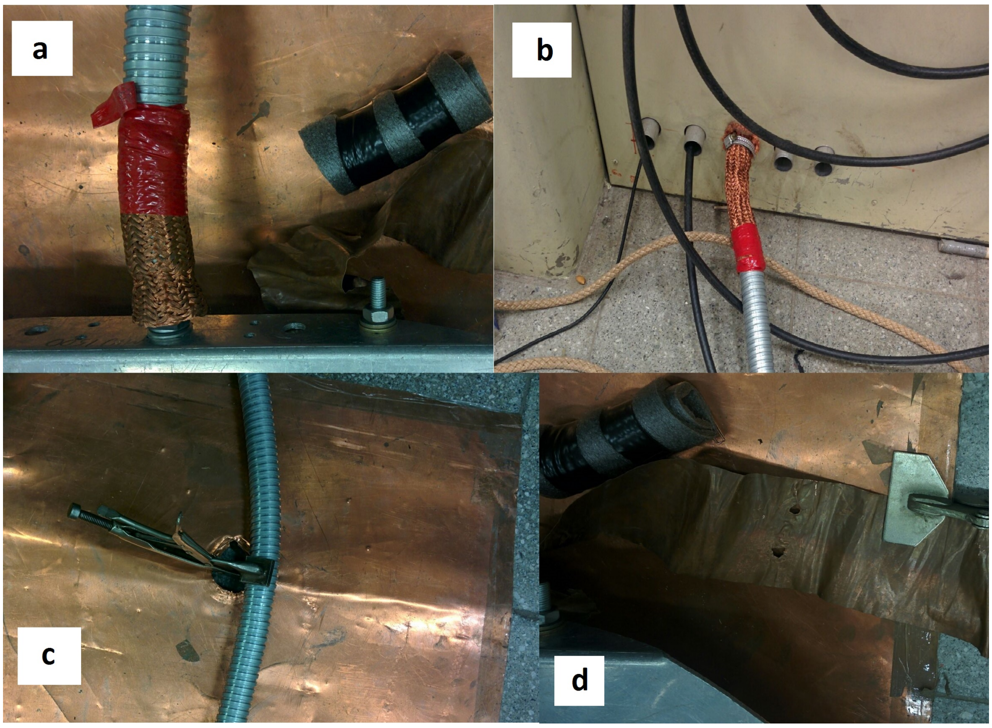


Figure 32: Extra cable shielding in measurement circuit A2. (a): No connection between the cable and pipe. (b): Pipe termination (not grounded). (c): Pipe grounded to the 500mm copper sheet. (d): Grounding of divider to the bottom 500mm wide copper sheet.

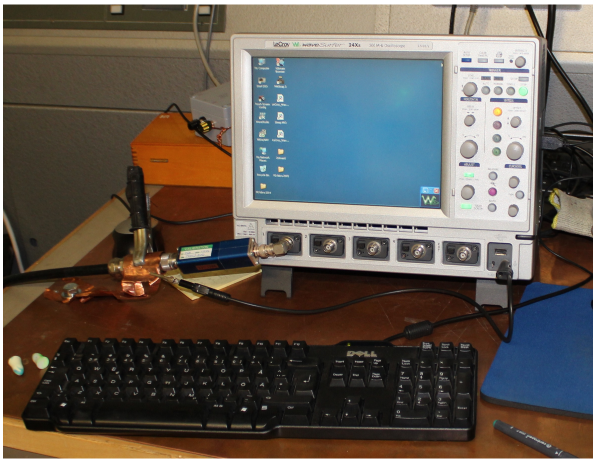


Figure 33: Instrument along with grounded cable and attenuator.

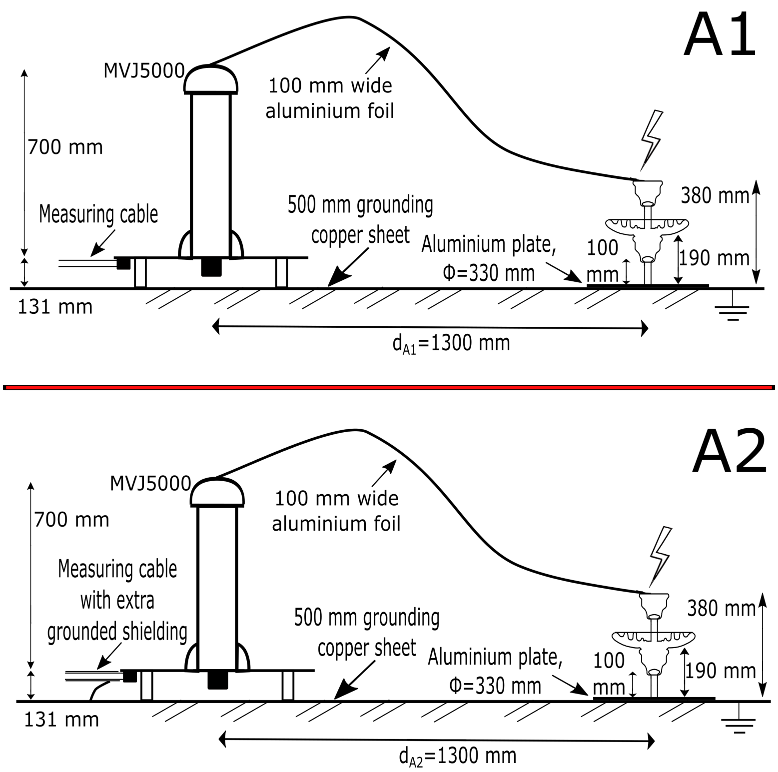


Figure 34: Measurement circuits A1 and A2.

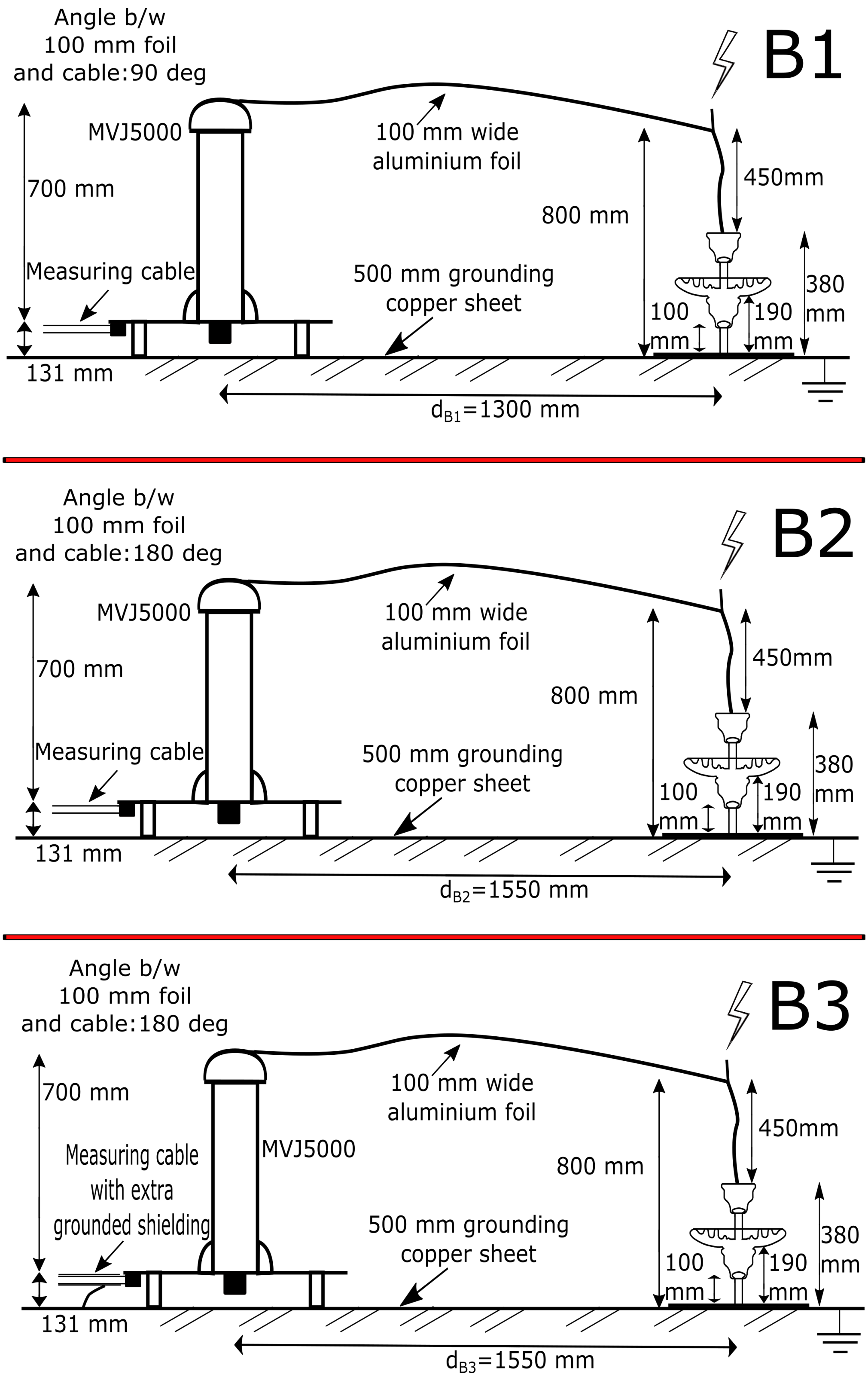


Figure 35: Measurement circuits B1, B2 and B3.

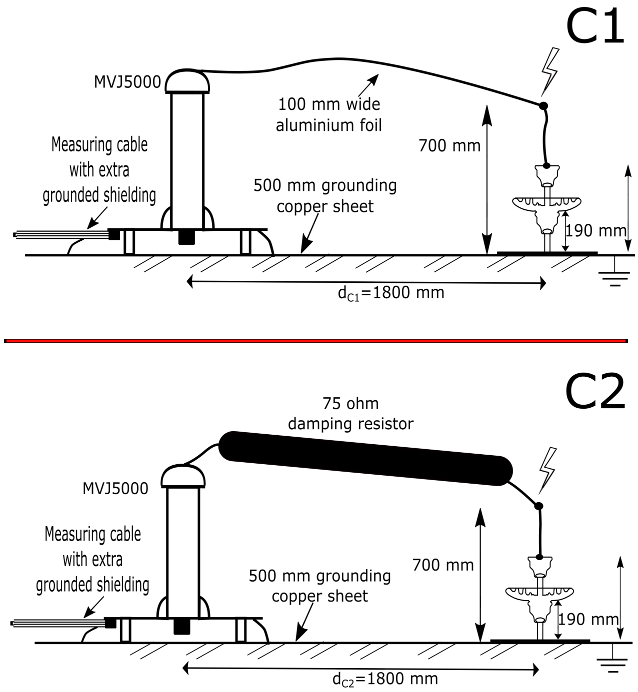


Figure 36: Measurement circuits C1 and C2.

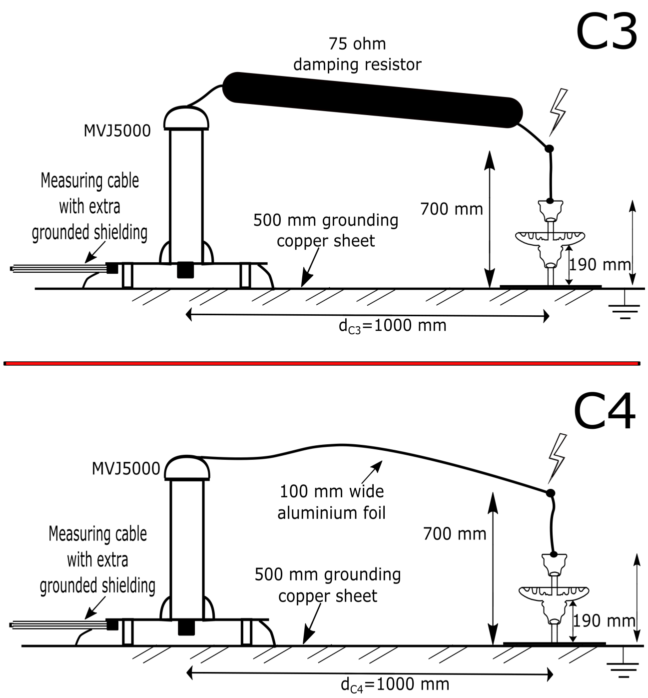


Figure 37: Measurement circuits C3 and C4.

5 Results and discussions

The data that were collected included impulse front time (T_1), time to half (T_2), peak voltage (test voltage peak value U_p) and steepness (S). Apart from that impulse shapes were also recorded in each test. From the measured data, statistical parameters like averages and standard deviations were computed.

5.1 Discussion on results of tested measurement circuits

5.1.1 Peak test voltage

The measured peak test voltages for various circuits with targets as 2.3pu, 2.8pu and 3.2pu of U_{50} are discussed here. It must be noted here that no insulator puncture was observed throughout the testing. Also, as evident below, not all circuits were tested with each of the above stated test voltages. Just for reference, all measurement circuits are shown in 4.6.

Goal: 2.3pu of U_{50}, with tolerance range of 227kV-250kV		
Circuit	**Measured avg. peak test voltage (kV)**	**No. of impulses with peak in the tolerance range (out of 10)**
A1	+243 −239	10 10
A2	+241 −240	10 9 (the missing one impulse was above the tolerance)
B1	+237 −240	10 9

Goal: 2.8pu of U_{50}, with tolerance range of 277kV-305kV		
Circuit	**Measured avg. peak test voltage (kV)**	**No. of impulses with peak in the tolerance range (out of 10)**
A1	+275 −285	6 9
A2	+276 −283	3 10
B1	+276 −284	0 10
B2	+271 −279	1 8
B3	+275 −298	4 10
C1	+274 −283	3 10

Goal: 3.2pu of U_{50}, with tolerance range of 316kV-348kV		
Circuit	**Measured avg. peak test voltage (kV)**	**No. of impulses with peak in the tolerance range (out of 10)**
B2	+314 −331	3 10
B3	+315 −330	3 10
C1	+300 −325	0 10
C2	- −317	- 8
C3	- −326	- 10
C4	+296 −326	0 10

All the missing impulses (out of 10), in the column stating the number of impulses with peak in the tolerance range, were actually below and outside the tolerance. Where they were above and outside the tolerance, it is mentioned separately.

So, with goal to achieve a test voltage of 2.3pu of U_{50}, only A1 managed to measure all 10 impulses for both positive and negative cases keeping the peak voltages well in tolerance range. A2 and B1 missed this scenario with 1 impulse each in the negative case. The average peak test voltages for all circuits were, however, within tolerance. With goal of test voltage of 2.8pu of U_{50}, none of the circuits managed to measure all 10 impulses having peak voltages within tolerance for positive case. The average peak test voltages in positive case for all circuits in this category were less than and out of the tolerance range by a margin of 1-6kV. All average peak test voltages for negative case were within tolerance. The only circuits that were close to achieving somewhat an ideal situation, as that of A1 2.3pu case, were A1 and B3.

With goal of test voltage of 3.2pu of U_{50}, only B2, B3 and C4 managed to stay well in good operating conditions. It's quite interesting that very few positive impulses with target test voltages of 2.8pu and 3.2pu stayed within test voltage tolerance. This could be due to possible flash-overs in front resistor assembly of the impulse generator.

One of the ideal requirements for impulse puncture testing to be reproducible is that the peak test voltage value should not vary much during a series of consecutive or successive impulses i.e. the standard deviation must preferably be lower than 5%. As seen from A, standard deviations of all test voltages for all types of measurement circuits were below 5%.

5.1.2 Effect of extra cable shielding and cable positioning

The results of measurement circuits A1 and A2 with target test voltage 2.8pu are compared in Figure 38 and Figure 39 to see effects of extra cable shielding. The schematics of A1 and A2 are shown in Figure 34. As seen, there isn't much difference between the two results. But it seems that the impulse front on the blue one (A2 2.8pu positive) is slightly better than the red one (A1 2.8pu positive) in Figure 38 since there is a sudden change in the front steepness of the red impulse. In the negative impulses, the effect of shielding is negligible, as seen in Figure 39.

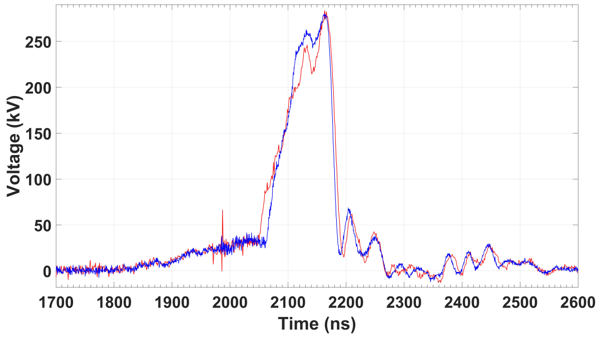


Figure 38: Effect of extra cable shielding. Red: A1, without extra shielding, U_p: 284kV, T_1: 159ns, T_c: 169ns, S: 1790kV/μs. Blue: A2, with extra shielding, U_p: 280kV, T_1: 89ns, T_c: 131ns, S: 3146kV/μs.

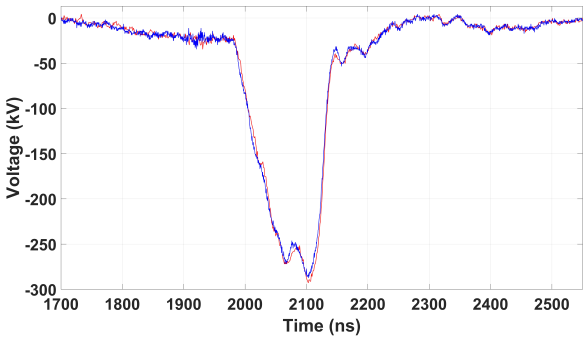


Figure 39: Effect of extra cable shielding. Red: A1, without extra shielding, U_p: -293kV, T_1: 98ns, T_c: 157ns, S: 2979kV/μs. Blue: A2, with extra shielding, U_p: -288kV, T_1: 98ns, T_c: 157ns, S: 2943kV/μs.

The rise times were calculated from the parts of impulses after they flashed over i.e from peak to the zero level. Using the rise times, bandwidths of measurement system in circuits A1 and A2 were found, as discussed in 2.5. For circuit A1 the bandwidths were 19MHz and 6MHz for +ve and -ve cases respectively. While the same for A2 were 23MHz and 10MHz, for the +ve and -ve cases respectively. So, using the extra cable shield has increased the measuring system's bandwidth. The bandwidths of both circuits were limited and less than the requirement of 60MHz approx.; therefore most impulses in this case were out of peak test voltage tolerance as seen in 5.1.1. The angle of the cable with the divider-insulator foil connection had no noticeable effect on the results.

5.1.3 Effect of HV damping resistor

A comparison of measurement circuits C1 and C2 with 3.2pu negative target test voltage, depicted in schematics as shown Figure 36, is shown in Figure 40 to study the effects of inserting 75Ω damping resistor between the divider and the insulator.

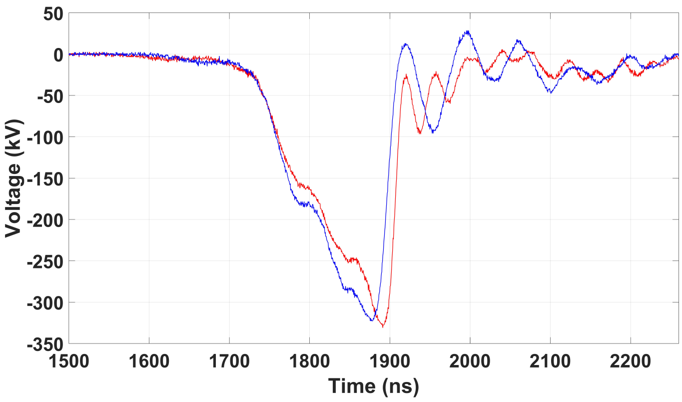


Figure 40: Effect of damping resistor. Red: C1, without damping resistor, U_p: -331kV, T_1: 196ns, T_c: 206ns, S: 1687kV/μs. Blue: C2, with damping resistor, U_p: -323kV, T_1: 162ns, T_c: 188ns, S: 1987kV/μs.

As seen from 5.1.1 in reference with Figure 40, with inclusion of HV damping resistor between insulator and divider, the number of impulses within the test voltage tolerance have decreased. The inclusion of the damping resistor, as seen in Figure 40, has smoothed out the impulse front slightly but along with that it has intensified the disturbances (oscillations) after the tail. The stronger oscillations after the tail could possibly be due to impedance mismatch after the added damping resistor which resulted in reflections. The bandwidths were computed from the tails of impulses (post-flash over). The bandwidths of C1 and C2 were 21MHz and 17MHz, respectively. The bandwidth of both circuits is limited and less than the 60MHz requirement, as elaborated in 2.5, but nevertheless, the inclusion of 75Ω damping resistor has decreased the measuring system bandwidth (without the instrument).

5.1.4 Effect of divider-insulator distance in different circuits

The distance between divider and the insulator was changed in different measurement circuits. Here a brief discussion is given on how this distance affects the results in these circuits. A comparison of measurement circuits B1 and B2, depicted in schematics shown in Figure 35, with 2.8pu negative target test voltage is shown in Figure 41. A similar comparison for measurement circuits C1 and C4, depicted in schematics shown in Figure 36 and Figure 37, with 3.2pu negative target test voltage is given in Figure 42, while the same for C2 and C3 is given in Figure 43.

In captions of figures, d refers to the divider-insulator distance.

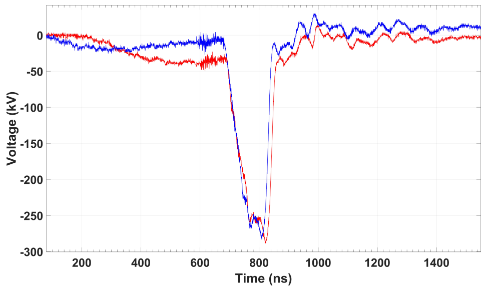


Figure 41: Effect of divider-insulator distance. Red: B1, d_{B1}=1300mm, U_p: -289kV, T_1: 140ns, T_c: 183ns, S: 2060kV/μs. Blue: B2, d_{B2}=1550mm, U_p: -283kV, T_1: 98ns, T_c: 154ns, S: 2888kV/μs.

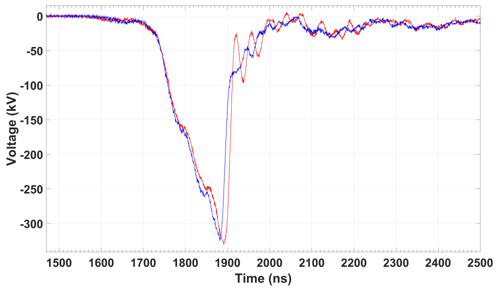


Figure 42: Effect of divider-insulator distance. Red: C1, d_{C1}=1800mm, U_p: -331kV, T_1: 196ns, T_c: 206ns, S: 1687kV/μs. Blue: C4, d_{C4}=1000mm, U_p: -320kV, T_1: 180ns, T_c: 197ns, S: 1805kV/μs.

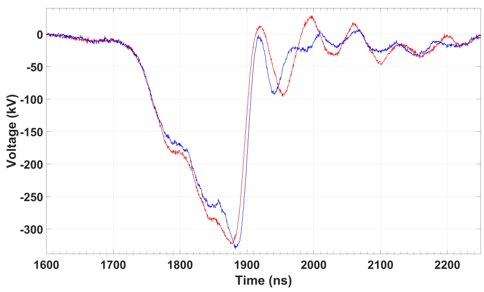


Figure 43: Effect of divider-insulator distance. Red: C2, d_{C2}=1800mm, U_p: -323kV, T_1: 162ns, T_c: 188ns, S: 1987kV/μs. Blue: C3, d_{C3}=1000mm, U_p: -331kV, T_1: 192ns, T_c: 203ns, S: 1720kV/μs.

With greater divider-insulator distance lesser number of impulses tend to stay inside the test voltage tolerances, as seen in 5.1.1. As far as the bandwidth is concerned, the measurement system improves the bandwidth slightly with the increase of the divider-insulator distance. In Figure 41, B2 has a greater bandwidth (14MHz) as compared to the B1 (9MHz). Same goes for C1 and C4, in Figure 42, with bandwidths of 21MHz and 6MHz respectively. However, a larger distance adds more oscillations and distortion, on both front and tail sides, in the overall impulse shape as compared to a smaller distance, as can be seen in Figure 41 and Figure 42. The inclusion of an HV damping resistor between the divider and insulator produced anomalous results in this regard i.e. bandwidth increased with reduced divider-insulator distance. C3 has a slightly bigger bandwidth than C2 i.e. 19MHz and 17MHz respectively. Nevertheless, all bandwidths for such comparison for all these circuits were still lower than the 60MHz requirement.

5.1.5 Limited bandwidths of measurement circuits

So far, it has been seen that all the discussed measurement circuits have bandwidths far lower than the required value of approx. 60MHz. Due to this reason, there would be many peak value errors in the measurements. There could be many reasons for this behaviour like LV arm to ground capacitance or the poor dynamic behaviour of the 10:1 attenuator connected between the cable and the instrument. The LV arm to ground capacitance amounted to 4pF as per its geometry, resulting in 40ps as RC time constant with LV arm resistance of 10Ω. This is negligible, therefore, the possible reason that could be limiting the bandwidth of the measurement circuits is the poor dynamic behaviour of the attenuator. Another scenario could be that the divider was placed at a large distance from the insulator in all of the measurement circuits while in [28] the divider was placed very close to the insulator. The large divider-insulator distances were kept to avoid direct flash-over from the foil connection to the MVJ5000's bottom aluminium plate. This poses a requirement to redesign the MVJ5000 in order to remove this constraint. Also, a new and properly calibrated attenuator should be used with the new divider design.

5.1.6 Step response from the measured impulses

Step response of the divider could also be determined from a chopped or flashed over steep front impulse. Principally, for measuring step response a very fast step voltage change is needed on the divider's HV lead. This step change could be done by either a step generator or a flash-over on the connected test insulator; with flash-over being the faster of the two. Also, IEC-61211 [1] recommends to measure the step response by keeping the system in the same configuration as in the puncture test, however without the test insulator. Two impulses, one from B3 and one from C1 which are shown in Figure 48, will be used to compute the step response of the divider in these specific circuit configurations and that too for two different nominal epochs. It can be seen from Figure 44 and Figure 45 that the first partial response times T_{alpha} for divider in circuit B3 were 19.16ns and 16.5ns. The same in case of C1 were 40.15ns and 26.89ns, as shown in Figure 46 and Figure 47. The overshoot is quite low in the presented step responses. Also, rise times were way higher than the approx. requirement of 6ns, pointing towards the fact that bandwidths were quite lower than the approx. 60MHz requirement. The drastic difference in T_{alpha} of B3 and C1 is possible due to the insulator-divider distance, amounting to 1550mm in B3 and 1800mm in C1. This poses another reason to redesign the divider by removing the bottom aluminium plate so that the divider's HV lead could be connected directly to the insulator without the need of any intermediate foil connection. After the voltage collapse in Figure 48, both impulses have reflections which were due to some impedance mismatch in the measurement circuit, probably due to the 10:1 attenuator.

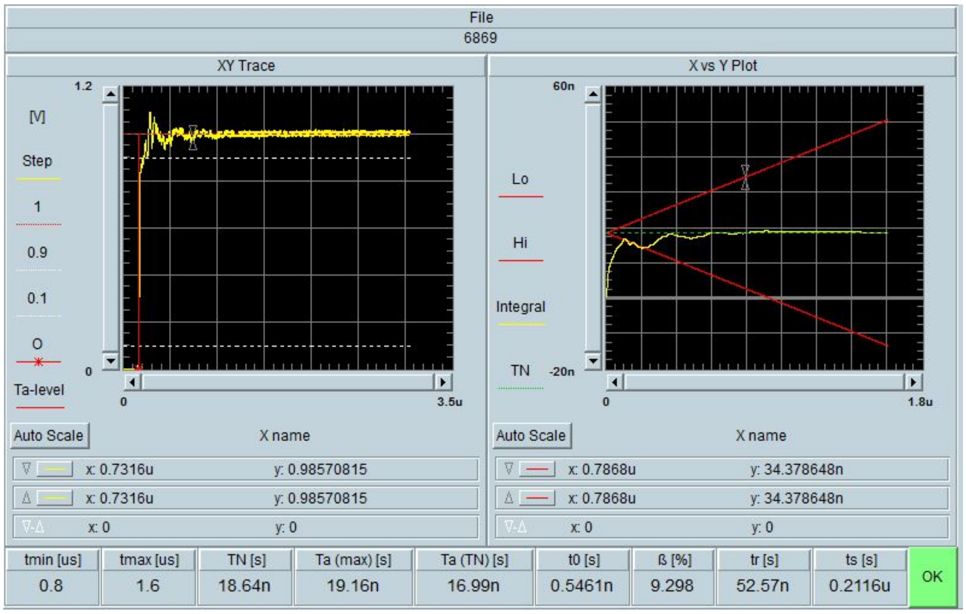


Figure 44: Step response in B3 - 2.8pu positive target voltage. $t_{min} = 0.8\mu$s and $t_{max} = 1.6\mu$s. Left graph: g(t). Right graph: step response integral T(t).

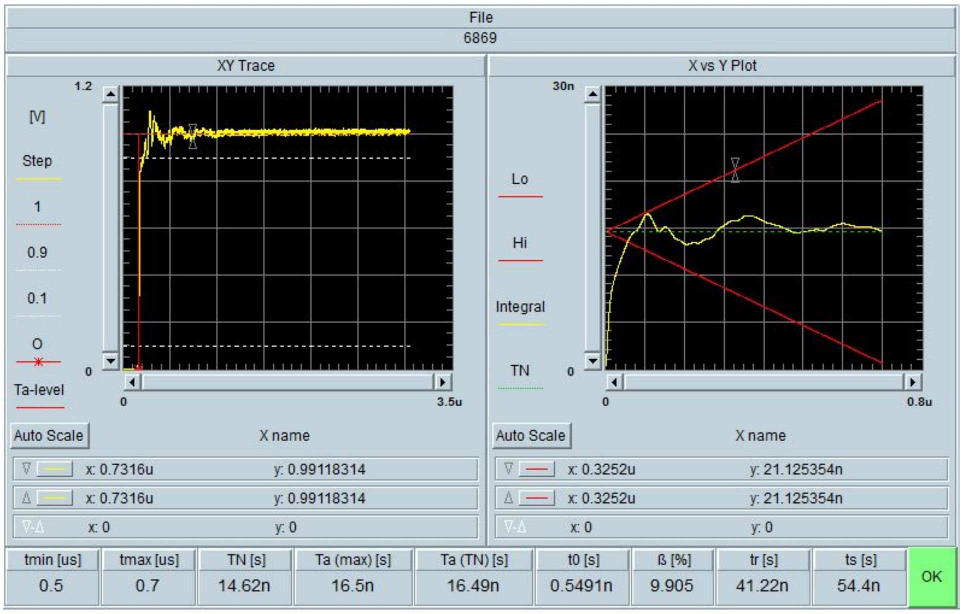


Figure 45: Step response in B3 - 2.8pu positive target voltage. $t_{min} = 0.5\mu$s and $t_{max} = 0.7\mu$s. Left graph: g(t). Right graph: step response integral T(t).

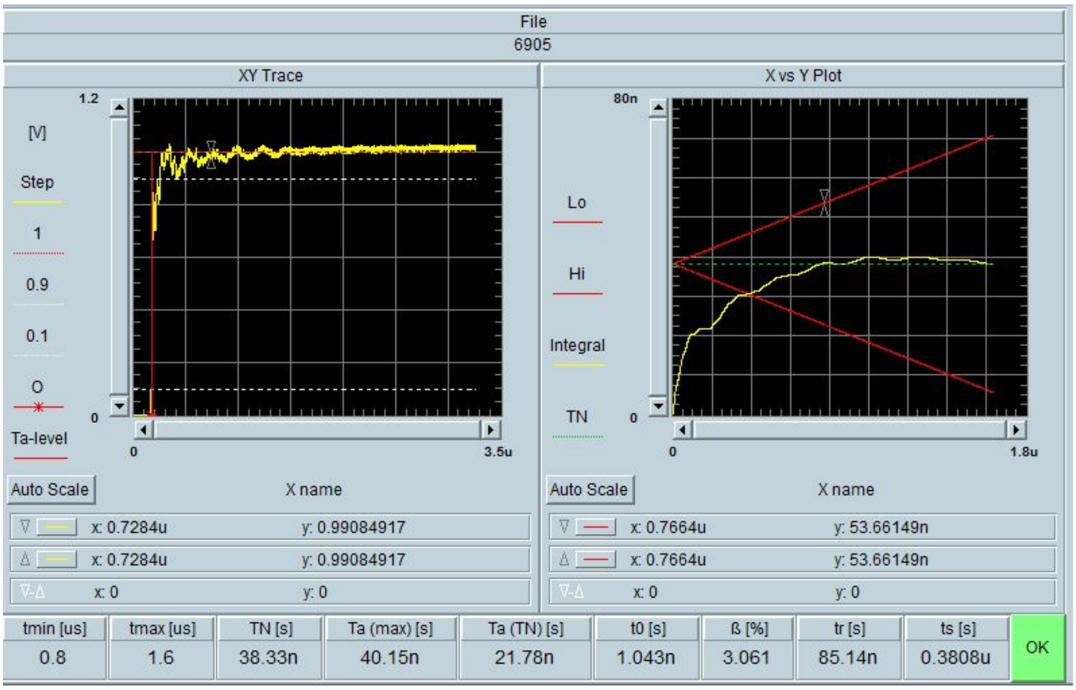


Figure 46: Step response in C1 - 2.8pu positive target voltage. $t_{min} = 0.8\mu$s and $t_{max} = 1.6\mu$s. Left graph: g(t). Right graph: step response integral T(t).

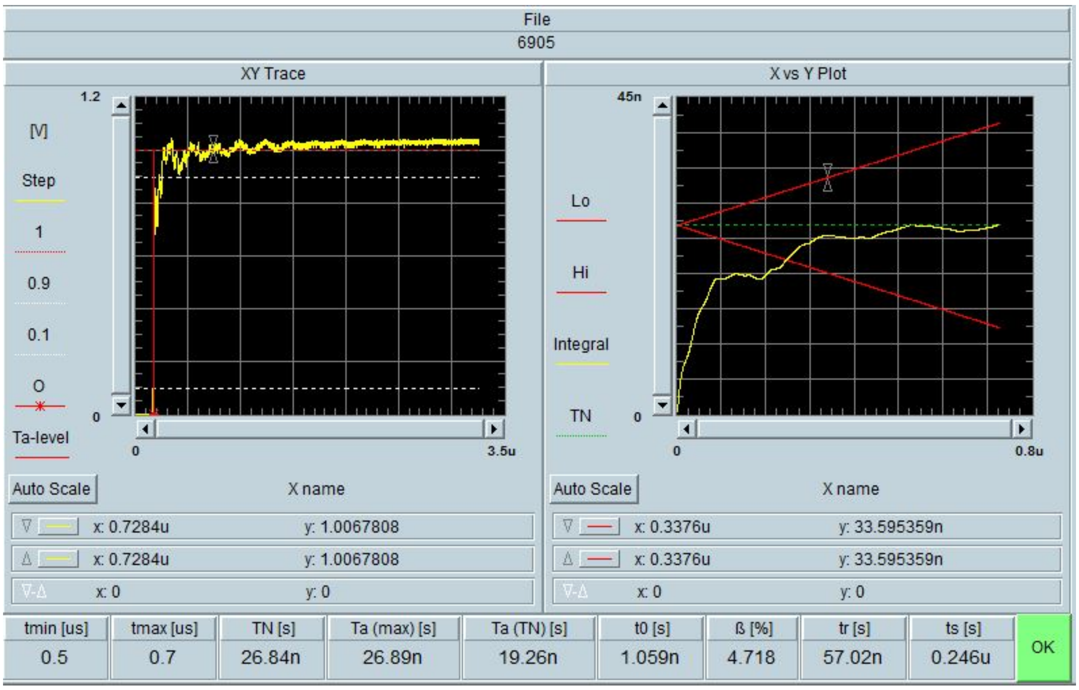


Figure 47: Step response in C1 - 2.8pu positive target voltage. $t_{min} = 0.5\mu$s and $t_{max} = 0.7\mu$s. Left graph: g(t). Right graph: step response integral T(t).

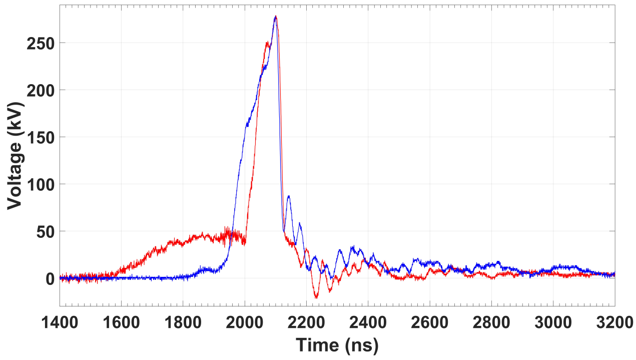


Figure 48: Red: B3 - U_p: 279kV, T_1: 101ns, T_c: 135ns, S: 2773kV/μs; Blue: C1 - U_p: 278kV, T_1: 193ns, T_c: 202ns, S: 1439kV/μs

5.1.7 Proposed novel algorithm and it's findings

A novel algorithm is proposed and is explained in adequate detail in C. The main functionality of the algorithm is to determine linearity of the steep front impulses measured by various measurement circuits and also calculate T_c as per IEC-60060-1 [2], as discussed in 2.1. The following are the findings of the algorithm:

- **Linearly rising front chopped property**: Using the proposed algorithm all the impulses (approximately 460 in number) were subjected to linearity test. None of the impulses were linearly rising front chopped in type A and B techniques. The time deviations were drastic and very random, the margin being as high as -15/+15 ns or so. C type circuits were a bit better. None of the positive impulses of both C1 and C4 were linearly rising front chopped. Same goes for negative impulses of C1, they missed being linearly rising front chopped by margin of as much as -3/+3 ns. The negative impulses of C4 were not linear but they missed it by a margin of as high as -2/+2. C2 and C3 had no linearly rising front chopped impulses. In short, C type circuits also had no perfect linearly rising front chopped impulses.

- **Instant of chopping and T_c**: The instant of chopping (IOC) should come immediately after the peak of the chopped impulse as per IEC-60060-1 [2], yet detailed investigation as seen in C shows that this is not the case. If the definition of IEC-60060-1 [2] is followed for finding the IOC then it can even come way behind the peak itself. The reason for this is the 10% (of the peak value) point on the impulse tail could make the 10%-70% line less steep, pushing the IOC to a point before the peak itself, hence resulting in an incorrect value of T_c. This could lead to a wrong calibration of the measurement system. This could also become a reason for wrong determination of impulse parameters by software written by personnels having less experience in this field.

5.2 Discussion on factors and effects due to generation circuits

5.2.1 Effect of different sizes of series spark or chopping gap spheres

Impulses from A2 and B3 measurement circuits are presented to study the effects of two different spark gap assemblies, in the generation circuit, on measured results. Insulator in A2 was stressed using gap of ϕ=250mm and d=100mm and in B3 it was ϕ=500mm and d=117mm. Here, the target test voltages in both of these circuits were 2.8pu positive. The circuits are shown in Figure 35 and Figure 34.

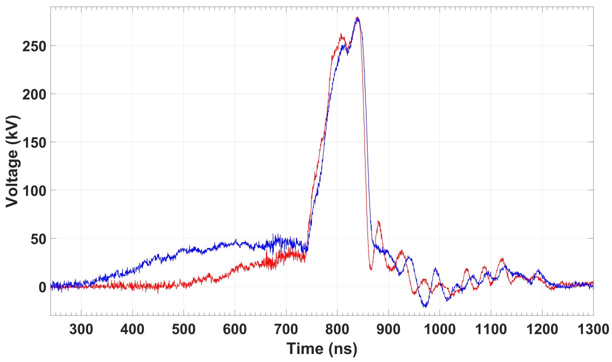


Figure 49: Effect of size of series spark gap spheres. Red: circuit A2, gap ϕ=250mm and d=100mm, U_p: 280kV, T_1: 89ns, T_c: 131ns, S: 3146kV/μs; Blue: circuit B3, gap ϕ=500mm and d=117mm, U_p: 279kV, T_1: 101ns, T_c: 135ns, S: 2773kV/μs.

When the impulse generator fires, an LI is fed by the generator to the series spark gap which chops it and a steep front impulse appears on the insulator which further gets chopped by the insulator flash-over. The original LI seems to be chopped at the tail in blue impulse while it is front chopped in red impulse. Due to the LI, a bulge like capacitive coupling, between the chopping gap and the divider/insulator, appears in the beginning of each impulses; in blue it beings at 300ns and ends when series gap fires at 730ns while in red it begin at 500ns and ends at 730ns. Hence, the overall profile of the capacitive coupling is bigger for blue due to larger sphere size while it is smaller for red. This observation also adds to the observations made by [35] that a non-encapsulated series sphere gap can produce disturbance, even before it gets fired, the intensity of which depends on the size of the spheres itself. Furthermore, this coupling could affect the determination of 30% point on the impulse front if it's more irregular and hence the front time, as said by [39]. The glitch near the peak shows the pre-discharges on the insulator body. Red impulse has a bigger glitch than blue because insulator is closer to spark gap in A type circuits as compared in B type circuits.

5.2.2 Effect of series inductor in generation circuit

[35] had suggested a generation circuit having an inductor, chopping gap and front resistor in series. It had given pretty good results with very less oscillations on the

front and the tail of the impulse. Insulator in some measurement circuits was stressed using similar generation circuit but without front resistor assembly and the chopping gap i.e. in C1 and C4. Results from measurement circuit C4 (shown in Figure 37) are compared with those from B3 (shown in Figure 35) to study the different effects of spark gap and non-spark gap generation circuits on the measured results. Here the target test voltage is 3.2pu positive in both.

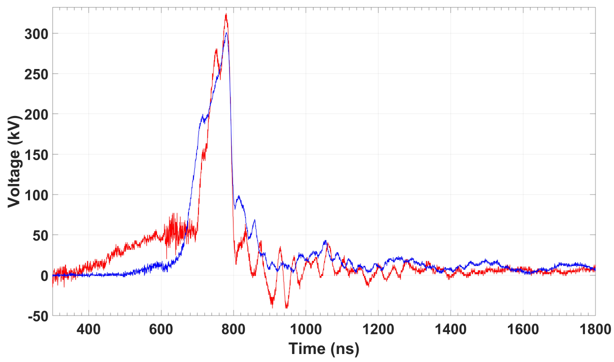


Figure 50: Effect series inductor instead of front resistor and chopping gap. Red: B3 with ϕ=500mm d=117mm spark gap, U_p: 325kV, T_1: 112ns, T_c: 122ns, S: 2912kV/μs ; Blue: C4 with 10μH series inductor, U_p: 301kV, T_1: 146ns, T_c: 158ns, S: 2057kV/μs.

It can be seen from Figure 50 that contrary to red impulse, there is no capacitive coupling (between sphere gap and the divider/insulator) like effect in blue impulse. Also, the impulse front in blue impulse is more linear and there were no pre-discharges near the peak. The presence of spark gap (red impulse) has shown effects like capacitive coupling, noise at beginning of front, insulator pre-discharges and large number of violent oscillations after the tail. There were some reflections in both impulses near the end and were because of mismatch of impedance in transmission.

5.2.3 Some general discussions

– **Charging voltage of the generator and steepness:** For any given target test voltage, it generally required a lower charging voltage for negative polarity as compared to the positive polarity, e.g. in C4 measurement circuit for achieving 3.2pu negative test voltage -100kV/stage was applied, while for positive polarity it was 150kV/stage. It is pointless to create any trend out of the charging voltage since every-time the circuit configuration is changed, the charging voltage has to be adjusted again via trial impulses to achieve the desired test voltage peak, as said in IEC-61211 [1] as well. In general, type A and B measurement circuits took higher charging voltages for generation circuit as compared to type C measurement circuits. Similarly, generation circuits for type A and B measurement circuits produced very steep impulses with average steepness as high as 3882.4kV/μs (in B1's 2.3pu neg case). Generation circuits for type C measurement circuits produced less steeper impulses with highest average steepness of 2028.7kV/μs (in C4's 3.2pu pos case).

- **Front time of impulses:** Impulses measured by all type C circuits had average front times around and above 150ns approximately. Impulses measured by type A and B circuits saw many variations in this regard with average front times as low as 64ns (in 2.3pu -ve case of B1) and as high as 130ns (in 3.2pu +ve case of B2).

6 Brief MVJ5000 characterization and design overhauling

After the detailed testing and discussing various possible circuits for impulse voltage puncture testing of glass/ceramic insulators, it was deemed important to make a characterization of the measurement system itself, that was used for all this research. The MVJ5000 divider was made after modifying an older version and calibrated in 2004. Since then no performance checks were made. Furthermore, no record of performance (RePe) was available. However, the RePe for the older version of MVJ5000 was available but even that didn't provide any insight into the performance parameters of the current version. Hence, it become very crucial to re-evaluate the performance of the divider at this stage. The lab didn't have the RePE for the divider but it did have the assigned scale factor for the whole measurement system, as used in testing. Being agile with testing various circuits without having a comprehensive RePe could provide us possible pointers for any future improvement in the measurement system design. Hence, that's why it was decided to move on with the testing. As far as the characterization of the measurement system is concerned, IEC 60060-2 [3] provides various tests/requirements/checks for an approved impulse measurement system. Among those, interference test was decided to be done first since it is needed to be done on an actual impulse puncture testing set-up, but with a little modification, as done in next sub-section. After interference test, step response test was done for determining the dynamic response parameters of the measurement system.

6.1 Interference Test

The main aim of interference test is to make sure that transmission system and measuring instrument receive acceptable limits of interference from the surrounding phenomenon like firing of sphere gaps etc. For this, guidelines as per IEC 60060-2 [3] were followed. The measuring cable was disconnected from the divider and was placed close to the output of the divider in the usual position. The input of the cable (the input connector) was short circuited and grounded. This was done by getting a spare female tri-axial connector and shorting its inner conducting terminal and the inner and outer shielding parts. This female connector was connected to the cable connector and this whole assembly was grounded to the bottom copper sheet. The output of the MVJ5000 was also short circuited and grounded. The extra shielding of the cable in the form of the corrugated metal pipe was grounded to the bottom copper plate. The remaining of the circuit was just like C4 and the generation circuit was also the same. The Figure 51 shows the set-up for the scenario.

Having all the test set-up ready, IEC 60060-2 [3] has directed to produce an interfering situation at the input of the divider via a disruptive discharge. Since the test set-up closely resembles C4, the 3.2pu negative polarity case, with average test voltage of -326kV and T_1=186ns, was decided to be used as the prospective disruptive discharge interfering condition at the input of the divider. The disruptive discharge must have the waveform that is representative of shape and voltage of discharge

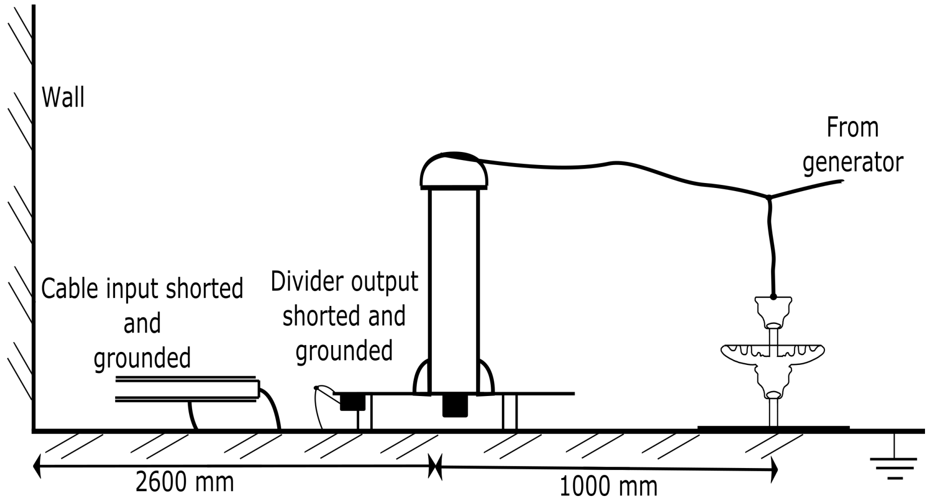


Figure 51: Interference test set-up.

applied to the divider during actual tests. C4 had very small standard deviation in peak voltage and time parameters, so it's good to assume that the fired impulses will not vary much and will stick around the mentioned average values. The only reason for assuming this thing is the fact that no other fast divider was available to measure the specifications of the impulses incident on the input of the MVJ5000. Hence, just like C4, some impulses were fired with the same charging voltage of -100kV/stage. The transmission system is supposed to record the output. The scale factor of the divider has changed to 1026 because the cable has been disconnected (from the divider side) while the attenuator's scale factor is the same i.e. 10:1.

The maximum and minimum amplitudes of interference measured were:

Impulse index	Max. +ve inter. amplitude (V)	Max. -ve inter. amplitude (V)
7000	2.303	-2.235
7001	2.385	-2.369
7002	2.116	-2.315
7003	2.223	-2.288
7004	2.305	-2.234

Table 2: Measured interference amplitudes. Impulse index is the text file name as saved in the oscilloscope.

As per IEC-60060-2 [3], the interference ratio is the maximum amplitude of the (measured) interference divided by the measuring system's output while measuring the test voltage. Furthermore, in order to pass this test, the maximum amplitude of the measured interference must be lower than 1% of the output of the measuring system while measuring the test voltage. Here, the maximum level of interference was observed in 7001 (+2.385/-2.369 volts). Since -326kV is the prospective discharge test voltage, this makes the interference ratio (in percentage) 0.75% (lower than 1%). Hence, the system has passed interference test as per IEC-60060-2 [3]. 6967 index impulse from C4 3.2 pu neg case is the closest to the intended prospective discharge test voltage. See Figure 52.

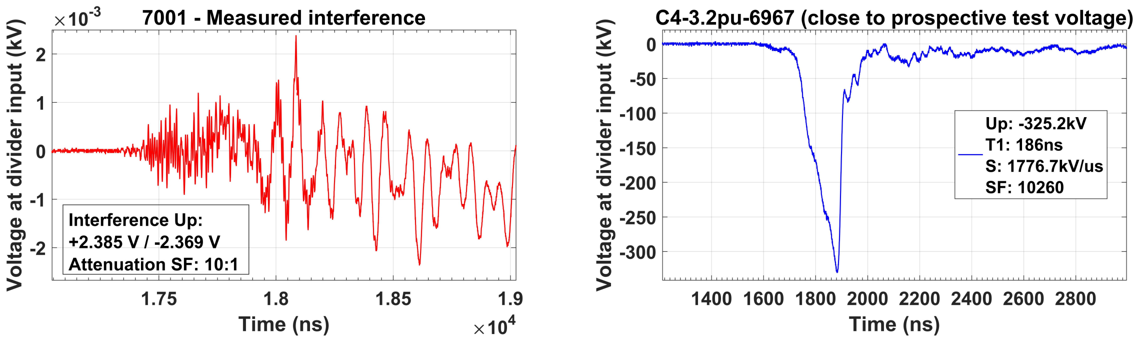


Figure 52: Left: 7001 interference waveform. Right: 6967 from C4 3.2pu neg case.

This test could be done in a better way using a tri-axial short circuit box type termination for the cable. The reason is that the box further shields the input of the cable from the interferences and gives a better judgement on the interference performance of the system. The effect of not using the box is quite visible in the above figure. The lowest frequency oscillation in 7001 is of approximately 71 kHz. Since the box wasn't available at that time so it was decided to do the test without it. Hence, this test should be repeated again.

6.2 Step Response

After the interference test, step response test was done for determining the dynamic response parameters. For the step response determination, the previous set-up was dismantled. The divider was then put in a horizontal position on the 500 mm wide grounded copper sheet on the floor, so that the distance between the sheet and the tube (enclosing the HV arm resistors) was 300 mm. The step generator was placed on a non-metallic/plastic material box structure so that the step generator's live terminal could be face to face with the divider's toroidal HV electrode. Once done, the connection was made between the two using a 30 mm wide and 50 mm long copper foil. The measuring cable of the divider was provided an extra shielding via the metal corrugated pipe, as done in previous circuits. The extra shielding was not connected to the cable in any manner. The step generator, the divider's bottom plate and the cable's extra shielding were grounded separately to the 500 mm copper sheet on the floor. The cable, attenuator and the instrument were grounded in the control room (the instrument end). The Figure 53 shows the test set-up for this.

Four different instruments were used to measure the step response, however only the most appropriate one is shown here i.e. the one done with LeCroy WaveSurfer 24Xs. The step measurements were done as single shot measurements, a preferred way is to measure 50 steps with averaging the results.

As seen in Figure 54, the divider shows very good rise time of 0.87ns and is a good choice for fast impulses with front times as low as 45ns, as seen in testing. In

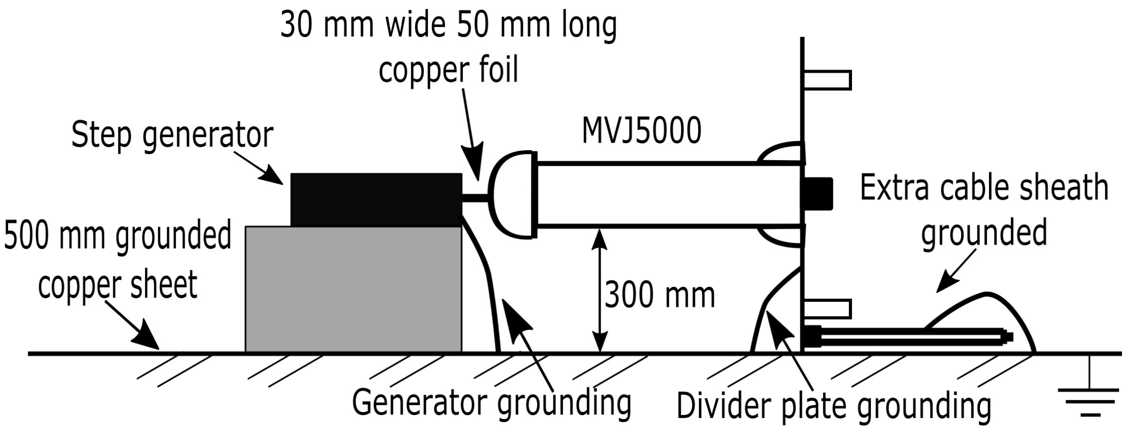


Figure 53: Test setup for step response.

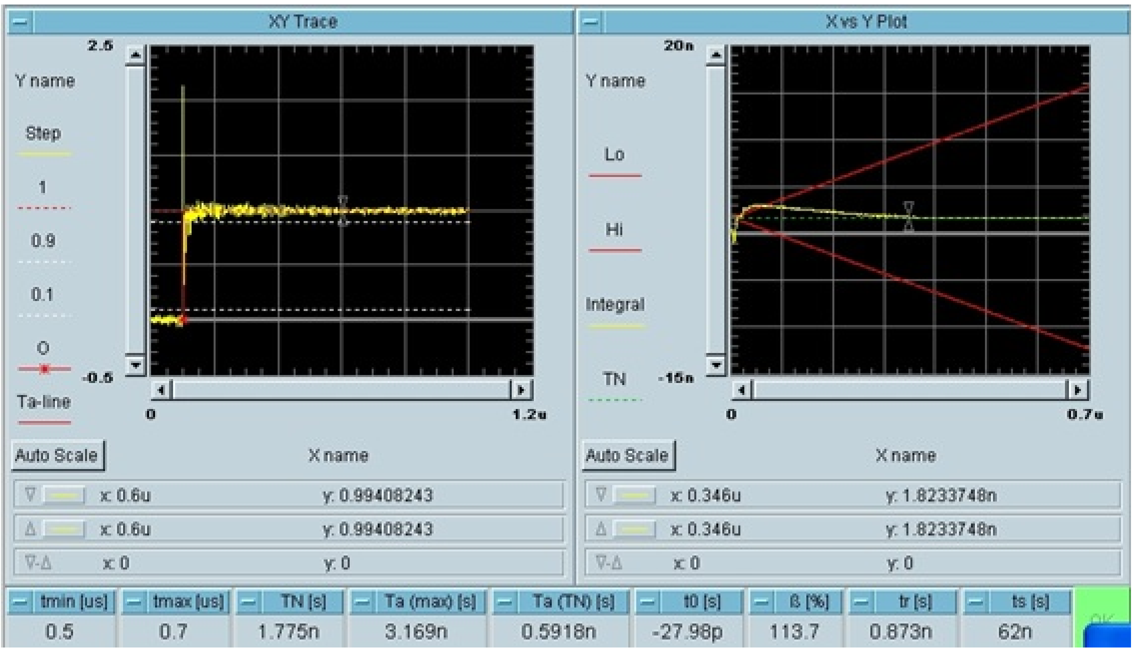


Figure 54: Step response with $t_{min} = 0.5\mu s$ and $t_{max} = 0.7\mu s$. Left graph: g(t) - major / minor = $0.2\mu s$ / $0.05\mu s$. Right graph: Step response integral T(t) - major / minor = $0.1\mu s$ / $0.025\mu s$.

5.1.6, step responses were computed using chopped steep front impulses and resulted in very poor dynamic behaviour of the system. Here, distance between the step change source and the voltage divider is very small, and has consequently resulted in very good dynamic performance of the divider in terms of T_α. Therefore, it confirms the possibility that the poor behaviour in 5.1.6 was due to the large insulator-divider distance. However, even with varying the nominal epoch as in Figure 55, overshoot is quite high: 113%-119%; first partial response time is 2.94ns to 3.16ns. The high overshoot was one of the reasons that step response was measured with multiple oscilloscopes with short loop between the divider and the step generator. This high overshoot could be attributed to the fact that the divider was not calibrated for a long period of time. The eventual drift and rough usage might have resulted in high overshoot. Moreover, from some old linearity data it was found that 300kV was the maximum full impulse for this design and impulses beyond this value would be prone to flash-over to bottom plate. Here, impulses with peaks as high as 330kV were measured without flash-over to the bottom plate. IEC-61211 [1] requires the fast divider to have $T_\alpha \leq$ 3ns for oscillating response but no requirement is mentioned for the overshoot(β). Fast divider in [35] has an overshoot of 90%. So 113%-119% is quite high. On close inspection of the divider, it was found that the tube of HV arm and also the bottom acrylic plate, which insulated the HV arm from the aluminium plate, were severely damaged. The entire testing was really very noisy (as well as illuminating due to sparks) because of insulator flash-overs therefore the possible reason for the damage could be an unobserved flash-over along the body of the tube itself. From this point onwards, it was impractical to continue any further experimentation due to the mentioned reasons.

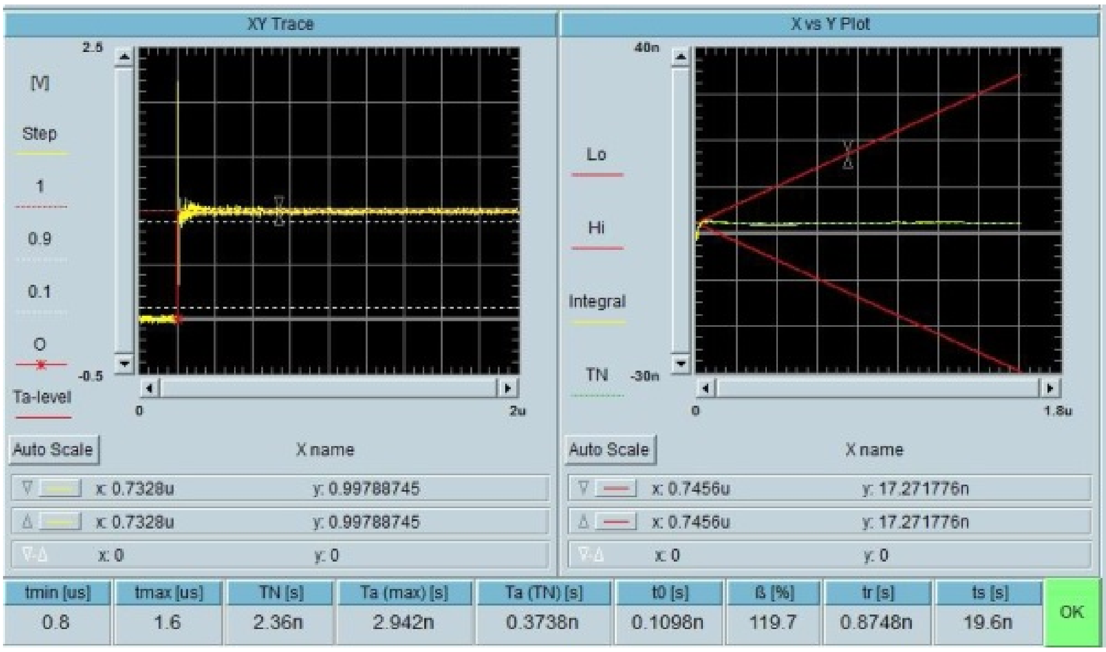


Figure 55: Step response with t_{min} = 0.8μs and t_{max} = 1.6μs. Left graph: g(t) - major / minor = 0.2μs / 0.05μs . Right graph: Step response integral T(t) - major / minor = 0.2μs / 0.05μs.

6.3 Transient analysis and discussion on disc resistors

The disc resistors come from HVR International and composed of mixture of alumina, various clays and carbon. They are pressed into required shapes and then fired in kiln. This results in ceramic carbon disc resistor and is 100% active material. They are normally sprayed by flame sprayed aluminium on flat surfaces for electrical contacts while anti-tracking film is applied on the periphery to enhance dielectric withstand strength [43]. The illustration for resistors used in MVJ5000 is in Figure 56.

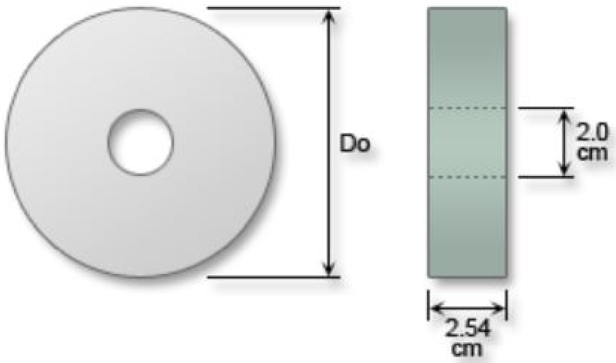


Figure 56: Disc resistor used in MVJ5000. D_o is 5cm for all disc resistors of MVJ5000 [43].

6.3.1 Thermal effect

The disc resistors have a negative temperature coefficient for resistance (TCR) and will show a decrease in resistance with temperature increase. Its unit will be %/°C temperature rise. The expression for TCR as per data-sheet [44] is given below.

$$TCR = 0.16 \times \mathrm{e}^{-(log\rho/1.4)} - 0.135 \tag{3}$$

where ρ is the resistivity. For one 200Ω disc resistor of HV arm ρ is 1300Ωcm while for 10Ω disc resistor of LV arm it is 65Ωcm. The range for TCR is -0.05% to -0.15% [44] generally, hence by using the above equation, for 200Ω resistor TCR is -0.12%/°C temperature rise while for 10Ω it is -0.09%/°C temperature rise. Graphs showing resistance variation with temperature are shown in Figure 57. Inductance is in nano Henry and therefore can be neglected but it must be kept in mind that lead inductances are always higher than this and can't be neglected.

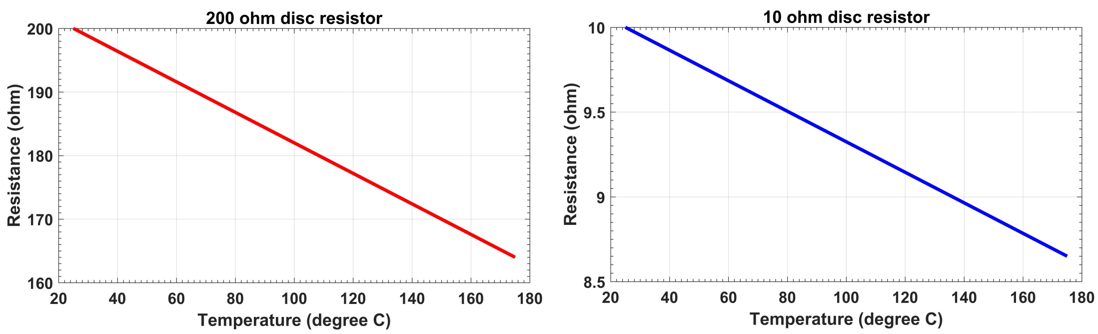


Figure 57: Variation of resistance of disc resistors with temperature starting from 25°C.

6.3.2 Effect of HV application

These disc resistors have a negative voltage coefficient for resistance (VCR), and will shown decrease of resistance with increased application of HV. This phenomenon is somehow muffled when disc resistors are connected in series to form an arm. The equation governing this phenomenon is [44]:

$$VCR = -0.62 \times \rho^{0.22} \tag{4}$$

where ρ is the resistivity.

The units for VCR are %/kV/cm and the normal range is -0.5% to -7.5%/kV/cm [44]. Specifically, by using above equation, for one 200Ω disc resistor of HV arm VCR is -3%/kV/cm while for 10Ω disc resistor of LV arm it is -1.6%/kV/cm.

6.3.3 Max. operation voltage withstand/cm of disc length

The maximum working voltage withstand of disc resistors per cm of disc length is given by the following equation [44]. This, however, only gives a value for discs in air stressed by a standard lightning impulse voltage. No guideline is given for steep front impulse voltages.

$$VWK = 4.3 \times \sqrt[1.2]{log(R/2.54 \times A/L)} \tag{5}$$

The unit for VWK is kV/cm.

A/L value for all disc resistors of MVJ5000 is 6.5cm [44]. Using the above equation, the withstand voltage for the MVJ5000, with 26 disc resistors of 200Ω each in the HV arm, comes out to be approx. 652kV of standard lightning impulse voltage. But, the withstand voltage corresponding to steep front impulses would be less. As mentioned previously, from old linearity data it was found that 300kV was the maximum full impulse for this design and impulses beyond this value would be prone to flash-over to bottom plate.

6.3.4 Transient analysis simulation

The capacitance to ground of the divider column can be calculated using the antenna formula proposed by Küpfmüller [40].

$$C_e \approx 24(pF/m) \times \frac{h}{log(h/d)} \tag{6}$$

For h = 700mm and d = 50mm (between HV arm and the bottom grounded aluminium plate), the capacitance to ground of comes out to be 6.36pF, this could be considered the HV arm's capacitance to ground. It was mentioned in 5.1.5 that the capacitance to earth of LV arm is approx 4pF. Using these values, the transient response is presented Figure 59. A pulse with rise time of 200ns, collapse time of 5ns and peak value of 300kV is used to develop the transient analysis simulation. The circuit used (Figure 58) is similar to one shown in Figure 23, it's again presented

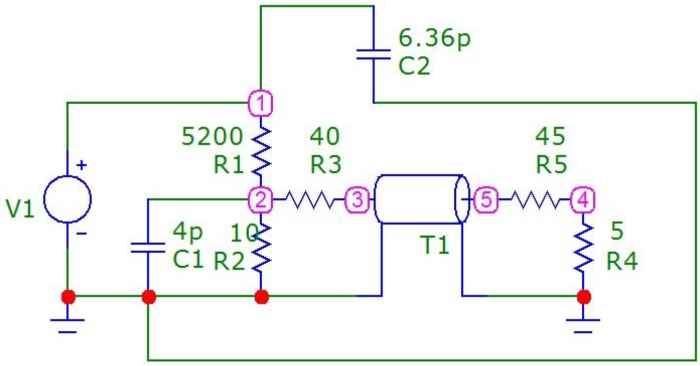


Figure 58: Circuit used for transient analysis simulation of MVJ5000.

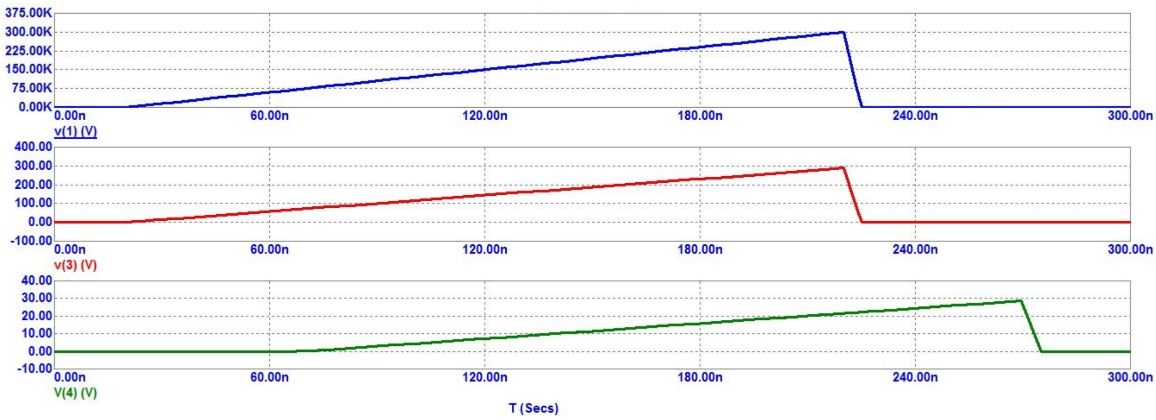


Figure 59: Transient analysis simulation. Voltage waveforms at nodes 1, 3 and 4 are shown.

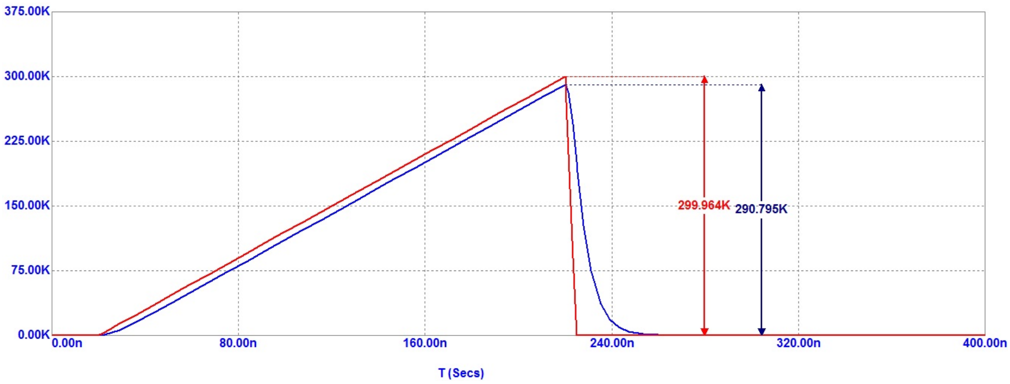


Figure 60: Effect of first order filtering. Red: input pulse with rise time of 200ns, collapse time of 5ns and peak value of 300kV. Blue: output

with various capacitances. The input capacitance of the attenuator is not used which, as per [23], is ≤12pF. The cable impedance is 50Ω with delay of approx. 50ns.

The first order filtering effect for divider is shown in Figure 60. The first order filter has a -3dB point at approx. 30MHz. This results in peak value error of about -3% in measuring the 200ns ramp with collapse time of 5ns. This further stresses the importance of high bandwidth of the divider i.e. value above requirement of 60MHz. This simulation could give wrong results if response of the system has heavy non-damped oscillations. This leads to positive error due to appearance of frequencies not present in the original test voltage. Also, the pre-discharges prior to flash-over of insulator are not considered here.

6.4 Brief design overhaul for MVJ5000

6.4.1 Newly proposed design (MVJ5000-N)

The damage of MVJ5000 along with its poor step response created a need for reconstruction from scratch. Furthermore, VTT needed to make a 600kV steep front divider for this project, which also called for a design overhaul. In this subsection, a brief design overhaul for MVJ5000 is proposed. The new design is named as MVJ5000-N in this text. This must be kept in mind that the proposed design doesn't involve electrical properties like scale factor or number of resistors for HV arm, the proposed design can however be helpful in achieving the final design as needed by VTT.

The following modifications are proposed:

- The bottom aluminium plate must be removed. This is because due to the plate, the divider has to be placed at a long distance from the test sample. The inductance of the HV lead and the divider-insulator foil connections kicks in. Furthermore, the bandwidth of the system goes way below 60MHz requirement and the T_{alpha} also becomes a lot more than the 3ns requirement. The modification is aimed at addressing these issues by allowing the divider to be hung in air or directly connected to the test object as seen in [28] and [35]. Also, the acrylic tube of HV arm must be removed for same reasons.

- The LV arm housing should be more modular, meaning that it should provide easier access to the components within. By modular design it is meant that components could be changed without much hassle. The existing housing is custom made with no design available at the moment. In order to make a fast divider whose copies could be made easily, the LV arm has to be redesigned. Furthermore, LV arm's design must be very much co-axial.

- The overall design must be easier to fabricate and dismantle.

- The cable and attenuator must be upgraded.

The Figure 61 gives the design of MVJ5000-N briefly and the parts are explained as below:

- **1**: It is a brass component and it supports the M16 threaded rod (through the 20mm deep hole, having threads on inner surface) on which HV arm resistors will be mounted. The top surface of this part will be in direct contact with the bottom most HV arm resistor. Also, there is a tube like protruded part on 1's bottom that goes through 2, 3, 4 and 5. The tube has threads on its inner side for bolt M8 (part 8).

– **2**: It is an acrylic plate that insulates 1 from 3 because 1 is of HV arm and 3 is the grounded upper lid for housing of the LV arm. It has a hole whose inner surface that has been profiled to allow the tube of 1 to pass through and perch properly.

– **3**: It is the threaded upper lid of the LV arm housing. It will also serves as a grounding point for the divider, a strip of copper (1mm to 1.5mm thick) will be inserted between 2 and 3 for this purpose.

– **4**: It is an acrylic tube that insulates tube of 1 from all the other parts (3 and 5).

– **5**: It is the LV arm resistor. It's upper surface is in contact with the grounded lid 3 while its lower surface is in contact with 6, which is a brass disc.

– **6 and 7**: 6 is a brass disc with a hole through its centre and 7 is a disc spring. Together, these two push up the resistor 5 using the bolt 8 (through 6 and 7). If all parts from 1 to 7 are put together and the bolt 8 is tightened, they will hold together firm.

– **8**: 8 is a standard M8 bolt with a hole in its head, where the banana plug 9 fits. Putting parts 1 to 7 together and putting bolt 8 in place, the connection could be made between the LV and the HV arms. The impedance matching resistors are connected at junction point of the HV and the LV arms, which is the bolt 8 itself. That's why a hole is made in the bolt to place a banana plug (9) for connection of impedance matching resistors.

– **9**: 9 is the banana plug, as told before. It makes the connection between 8 and 10.

– **10**: 10 is a brass disc with a central hole for banana plug. The hole has threads on inside where banana can be fixed. There are threaded holes for screws on the other surface of 10 as well to which impedance matching resistors will be connected. There are also some other threaded holes where nylon stand-offs (11) can be fixed using screws. 10 also acts as the same LV-HV arms junction point, just like the banana plug 9 and the bolt 8 because these will be in contact with each other.

– **11**: Nylon stand-offs that insulate 10 from 13 because 13 is grounded bottom lid of LV arm housing.

– **12**: 12 is the hollow and cylindrical LV arm casing/housing in which all other LV arm components are located. It is grounded.

- **13**: 13 is the bottom lid for 12. It is also grounded. It also has a hole in the middle for mounting the connector for the measuring cable.

- **14**: It is the stack of HV arm disc type resistors, piled up on 16 which is the M16 threaded rod. Each HV arm resistor is similar to the LV arm resistor in dimensions.

- **15**: Toroidal HV electrode or simply the HV lead. It is kept in place by bolts and washers that are coupled to the 16 (M16 threaded rod). The connection to the insulator will be made at this point.

- **16**: M16 threaded rod on which HV arm resistors are mounted. It is made of an insulating material like acrylic. The rod goes into 1 and stays intact through the inner threads of hole in 1 and also outer threads of M16 rod itself.

The design was made in AutoCAD and separate drawings of all the parts are given in B.

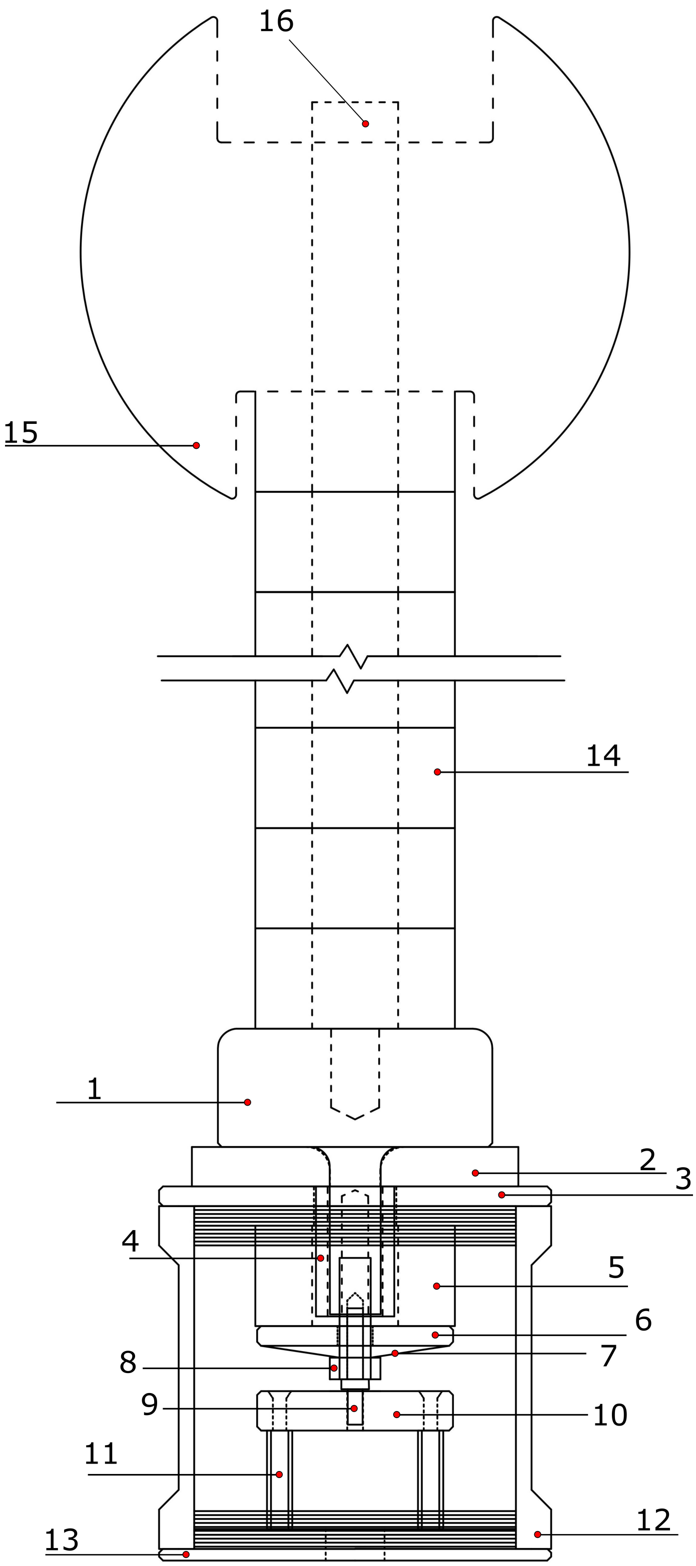


Figure 61: Complete proposed MVJ5000-N divider design including HV arm and LV arm.

6.4.2 Constructed MVJ5000-N

The newly constructed MVJ5000-N is shown in Figure 62.

Figure 62: Constructed MVJ5000-N.

The attenuator is 50:1, has a nominal impedance of 50Ω and has a frequency range of DC to 3GHz. The disc resistors are, however, of the same specifications as in MVJ5000. MVJ5000-N has scale factor of 100000:1 (600kV:6V) at 50Ω.

7 Conclusions and future work

7.1 Overview

7.1.1 Research survey

- The survey was sent to as many as 50 international HV labs, research centres and testing facilities. Out of those 50, only 7 replied. Out of those 7, only 5 performed impulse puncture testing on ceramic/glass insulators in air as per IEC-61211 [1].

- The responders faced many problems regarding generation of steep front impulses, their measurement, interferences, poor dynamic response of system, stray capacitances and stray inductances.

- The results, therefore, proved the need of doing a detailed research and experimentation on practices and procedures of impulse puncture testing.

7.1.2 Measurement circuits

- **Mounting arrangements and grounding:** A U120BL cap and pin insulator was used as test sample and was mounted using ball and socket contraption with cap side down and was fixed in an aluminium plate which was then placed on a 500mm wide copper grounding sheet. This sheet also served as a grounding for divider, extra cable shielding and the load capacitor of the generator. The mounting arrangements of the insulator and the grounding were kept constant throughout the testing while other factors like divider-insulator distances, cable shielding etc. were varied.

- **Measurement system:** The measurement system comprised of a fast and small MVJ5000 divider, a tri-axial cable and a 200MHz, 8bit digitizer and capable of sampling rates of 2.5GS/s. Between the cable and the instrument a 10:1 resistive attenuator was used.

- **Peak test voltage:** As seen from 4.6 and 5.1.1, for target test voltages of 2.3pu of U_{50}, A1 measurement circuit measured all impulses of both polarities within the test voltage tolerance range. For 2.8pu positive case, all the tested measurement circuits measured a lot of impulses that were out of tolerance. For 2.8pu negative case almost all the tested circuits, with the exception of a few, measured almost all impulses within the tolerance. Exactly the same pattern as 2.8pu was followed by those measurement circuits which were tested for target test voltage of 3.2pu. It's worth noting that standard deviation of observed test voltage of all impulses for any given circuit was below 5%.

- **Cable shielding and positioning:** As seen from 5.1.2, using a tri-axial cable along with extra shielding in form a metal corrugated pipe has proved to slightly reduce oscillations and disturbance on the impulse front. It has also resulted in increased bandwidth, by an amount of 4MHz approx., of the measurement system (without the instrument). The spatial angle of cable with the insulator-divider connection foil has no noticeable effect on the results. The extra shielding was not connected to the cable in any way; however it was grounded to the 500mm copper sheet near the divider. The cable and attenuator were grounded along with instrument on the instrument end.

– **HV damping resistor at input of divider:** As seen from 5.1.3, adding an HV damping resistor between insulator and divider smoothed out the oscillations on the impulse front but also intensified disturbances on the tail side due to possible mismatch of impedance that resulted in reflections. The addition of HV damping resistor in the measurement circuit further decreased the bandwidth of the measurement system (without the instrument) by an amount of 4MHz approx. Also, with addition of damping resistor lesser number of impulses tended to stay within the test voltage tolerance.

– **Compactness of measurement circuit:** With increased divider-insulator distance, lesser number of impulses stay within peak test voltage tolerance, as seen in 5.1.1 and 5.1.4. The increased distance also added more oscillations on front and tail side. However the measurement system bandwidth increased, by an amount of much as 15MHz, when divider-insulator distance is increased.

– **Limited bandwidths and step response from measured impulses:** Measured impulses from all measurement circuits were used to determine the step response and system bandwidth (without instrument) since the insulator flashover serves as a step change at the divider input. It was found that bandwidth of all circuits was limited and lower than the minimum required bandwidth of approx. 60MHz (or rise time of approx. 6ns or T_{alpha} of 3ns) as per IEC-61211 [1]. T_{alpha} was way higher than the 3ns requirement, in range of 16-40ns. Although the system bandwidth increased slightly by increasing divider-insulator distance, yet the anomalous behaviour found here in step responses is due to large divider-insulator distances as it was confirmed by step response done with step generator with very small divider-generator distance i.e. it had very good response parameters as seen in 6.2. Large peak value errors would be in measurements due to these limited bandwidths. This was one of the reasons that a new divider design was needed so as to remove the bottom aluminium plate in order to place the divider's HV toroid electrode directly in contact with the insulator without any foil connection. The other reason was that the divider broke during the testing.

7.1.3 Generation circuits

– **With series chopping/spark gap:** Two kinds of such generation circuits were used, one with sphere of ϕ=250mm and d=100mm and other with ϕ=500mm and d=100mm / 117mm. Physically, these were complicated to construct and produced impulses that were very steep (average value as high as 3882kV/μs) with low values for front times (average value as low as 64ns). They also produced creep-age like effect in the beginning of the impulse due to capacitive coupling between sphere gap and the divider/insulator. The amount of this effect increased with size of spheres.

- **Oscillatory circuit:** This generation circuit used a series inductor of 10μH. This was less complicated physically and no capacitive coupling effect was observed in impulses. The impulses produced were less steep (average values as high as 2124kV/μs) as compared to generation circuit using series chopping/spark gap, with higher values of front times (average values as low as 146ns). Lesser oscillations/disturbances were observed in the impulses in this case.

7.1.4 Novel algorithm

Although steepness is not the stress criteria for impulse puncture testing as per IEC-61211 [1], yet it was analysed using a novel algorithm as proposed in C. The algorithm was proposed to improve results wrongly obtained from MS Excel. The summary is:

- **Impulse front linearity:** None of the impulses in the entire course of testing was perfect linearly rising front chopped as per definition in IEC-60060-1 [2], although some impulses were wrongly termed as linear via calculation in MS Excel, as explained in C.

- **T_c determination as per IEC-60060-1:** If T_c is determined as per definition in IEC-60060-1 [2] then it could give a wrong instant of chopping (IOC) for steep front HV impulses i.e. IOC could come even before the peak of the impulse itself. This leads to wrong impulse time parameter calculation in the software. If an inexperienced lab personnel uses this standard to develop measurement software for instrument then chances are that they will get wrong values of T_c from that software. This is the reason, this finding is presented here. This finding was a bonus in addition to original purpose of the algorithm creation.

7.1.5 MVJ5000-N divider design

Due to a large bottom aluminium plate in MVJ5000 divider had to be placed 1000-1800mm away from insulator to avoid flash-over to the plate. This resulted in low bandwidth of the system, as already explained. The divider had passed the interference test as per IEC-60060-2 [3]. It was also put to a step response test with a very small divider-step generator distance. The response parameters were quite good (T_{alpha} was 2.94-3.16ns) but with a very high overshoot. Also, the divider got broken during the testing. All these factors called for an improved divider design to address the project goals in a better way. The new proposed design, named as MVJ5000-N, is aimed at improving the dynamic response of the system and allowing the divider to be placed very close to the insulator via removal of bottom plate. Moreover, the design is modular with the effect that it could be mass produced for measuring voltages up-to 500-600kV and rise times below 200ns (front times below 250ns) [10].

7.2 Recommendations for a suitable puncture testing methodology

– For generation circuit, sphere gap type circuits produce steeper HV impulses as compared to non-sphere gap type. Encapsulated sphere gap can be used to reduce oscillations/disturbances in the impulses. Various sizes of spheres and gaps can be used, however.

– The grounding for the measurement circuit should be provided through a wide (at-least 500mm wide) and long (3-5 metres) copper sheet, grounded to lab's common earth. It should be fully tried to ground all equipment at a common point so as to avoid earth loops, circulating currents and unnecessary inductances. All kinds of connections must be made through metal foils (50mm wide).

– The cable must be shielded by providing an extra shield in form of corrugated metal pipe which should be grounded to the common ground. This extra shield must not be in contact with any of cable's metal contacts. The cable, attenuator and the instrument should be grounded together on the instrument end.

– A resistive divider made of solid discs is the most suitable one for steep front HV impulse measurements. The divider must be capable to withstand 400-500kV of steep front impulses with front times of as low as 60-100ns. The peak voltage rating, however, highly depends on the type of insulator to be tested. The step response parameters must be strictly achieved in order to keep measurement uncertainties to required limits.

– Depending on the nature of divider, adequate distance must be there between divider and insulator. However, a large distance could result in oscillations due to long connection foils and lead inductances. The large distance could also result in low system bandwidth, which is not desirable.

– A fast instrument, at-least 200MHz 8Bit with sampling rates of around and above 2.5GS/s, is recommended.

– Any extra damping resistors, that were not a part of divider calibration, must be avoided while measuring such fast impulses.

7.3 Future work

There could be many suggestion for future works. Some of them are given below:

- The MVJ5000-N divider must be tested duly. The results from MVJ5000-N in terms of step response measurements and full steep front HV tests must be compared with the results found from MVJ5000. This further includes testing of MVJ5000-N divider in various positions relative to the test object i.e. different measurement circuits. A faster oscilloscope is recommended.

- Field simulations or Finite Element Model of MVJ5000-N must also be done in COMSOL Multi-physics software in order to optimise its operation.

- The definition for evaluating instant of chopping (IOC) and T_c, as per IEC-60060-1 [2], must be revised to take into account the anomalous behaviour of chopped steep front HV impulses.

- Cable shielding in terms of ferrite beads can also be tried, in addition to the normal corrugated pipe type one.

- The software for evaluation of impulse parameters must be investigated in more detail.

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A Details of all Impulses

A.1 With series spark gap

Designation	Test setup	U_{peak} /kV stdev/%	T_1/ns stdev/%	Steepness, kV/µs stdev/%
A1	Impulse generator, sphere gap ϕ 250 mm, d 100 mm, Cable and instrument grounded in instrument end. Insulator - divider 100 mm Cu-foil, distance 1.3 m Goal 2.3x	+243 kV *) 2.1 %	80 ns 14 %	3098 kV/µs 14 %
		-239 kV 1.3 %	113 ns 15 %	2148 kV/µs 14 %
A1	Same as above Goal 2.8x	275.20 kV *) 2.23 %	114 ns 36.3 %	2743.93 kV/µs 37.7 %
		-285 kV 1.7 %	102.7 ns 17.8 %	2833.6 kV/µs 12.5 %
A2	Same as A1. Extra cable sheath, grounded to Cu-plate, not connected to cable earth Goal 2.3x and 2.8x	241.12 kV 1.91 % +275.8 kV *) 1.3 %	87.3 ns 44.9 % 83.8 ns 23.7 %	3071.98 kV/µs 26.25 % 3460.3 kV/µs 23.4 %
		-239.93 kV 2.19 % -282.5 kV 1.1 %	109 ns 12.4 % 106 ns 18.4 %	2235.064 kV/us 11.26 % 2724.6 kV/µs 12.7 %
B1	Sphere gap ϕ 500 mm, d 100 mm. Cable in 90° from conductor line. Cable sheath removed. Goal 2.3x and 2.8x	+236.6 kV *) 2.0 % 275.53 kv 0.91 %	70.1 ns 22.7% 92.8 ns 12.9 %	3519.8 kV/µs 20.4% 3012.53 kV/µs 12.34 %
		-239.8 kV 3.1 % -283.86 kV 1.06 %	64.1 ns 20 % 102 ns 13.2 %	3882.4 kV/µs 20.5 % 2803.69 kV/µs 9.73 %
B2	Same as B1. Cable and conductor in the same line. Goal 2.8x	-	-	-
		-283 kV note: 1 impulse	101 ns	2818 kV/µs
B2	Sphere gap ϕ 500 mm, d 117 mm. Goal 2.8x	+271 kV *) 2.0 %	98 ns 20 %	2857 kV/µs 20 %
		-279 kV 1.0 %	92 ns 4.4 %	3053 kV/µs 3.9 %
B2	Same as before. Goal 3.2x	+314 kV *) 2.0 %	130 ns 32 %	2554 kV/µs 20 %
		-331 kV 1.6 %	106 ns 14 %	3187 kV/µs 13 %

Figure A1: Double loop circuits. x means per unit, as in 2.0x, 2.3x, 2.8x and 3.2x.

B3	Sphere gap ϕ 500 mm, d 117 mm. Cable turned to conductor lane. Insulator - divider distance 1.55 m, extra cable sheath grounded to Cu-plate, not connected to cable earth. Goal 3.2x. Damping resistor was broken.	+315 kV* 1.62 % -329.6 kV *) 1.6 %	127 ns 32.3 % 108.9 ns 9.6 %	2623 kV/µs 18.17 % 3050.5 kV/µs 9.0 %
B3	Same as before, R_{du} changed to 2x300 Ω (two in parallel, two in series) Goal 2.8x	+274.8 kV 1.4 %	92.7 ns 14.8 %	3027.3 kV/µs 16.2%
		-297.8 kV 1.1 %	90.6ns 5.8 %	3297.4 kV/µs 7.0 %

Figure A2: Double loop circuits - continued. x means per unit, as in 2.0x, 2.3x, 2.8x and 3.2x.

A.2 Without series spark gap

Designation	Test setup	U_{peak} kV stdev/%	T_1 ns stdev/%	Steepness kV/µs stdev/%
C1	No sphere gap. Modified LI-circuit. Insulator - divider 1.8 m. Extra cable sheath. Goal 2.8x and 3.2x	273.94 kV 1.08 % 299.54 kV 1.73 %	189 ns 2.03 % 149 ns 3.21 %	1452.80 kV/µs 1.35 % 2017.52 kV/µs 1.83 %
		-283.2 kV 0.8 % -325.10 kV 0.81 %	228.1 ns 1.2 % 195 ns 0.83 %	1241.7 kV/µs 1.6 % 1671.43 kV/µs 1.11 %
C2	75 Ω damping resistor of divider added. Goal 3.2x	-	-	-
		-317 kV 1.4 %	149.8 ns 7.0 %	2124.2 kV/µs 6.0 %
C3	Same as C2. 75 Ω damping resistor. Short loop. Insulator - divider 1.0 m. Goal 3.2x	-	-	-
		-326 kV 1.0 %	192.5 ns 1.3 %	1694.5 kV/µs 1.1 %
C4	Same as C1, short loop, insulator - divider 1.0 m. Goal 3.2x	+296.3 kV 1.0 %	146.1 ns 2.4 %	2028.7 kV/µs 1.8 %
		-325.8 kV 0.9 %	185.6 ns 1.3 %	1784.3 kV/µs 0.7 %

Figure A3: Without spark gap and the front resistor. x means per unit, as in 2.0x, 2.3x, 2.8x and 3.2x.

A.3 Summary of representative circuits

U_{CH} kV	Up kV	T1 ns	Steepness kV/μs	Impulse No.
105	-300.5	79.3	3788	6875
105	-303.9	84.8	3585	6876
105	-298.7	88.2	3386	6877
105	-297.2	91.9	3234	6878
105	-295.4	95.5	3094	6879
105	-291.9	94.3	3096	6880
105	-296.9	94.3	3149	6881
105	-297.1	95.5	3112	6882
105	-295.3	92.1	3207	6883
105	-300.6	90.5	3323	6884
avg	**-297.8**	**90.6**	**3297**	
stdev/%	**1.1 %**	**5.8 %**	**7.0 %**	

Figure A4: With sphere gap - B3 2.8pu negative summary.

U_{CH} kV	Up kV	T1 ns	Steepness kV/μs	Impulse No.
150	296.7	150.5	1970.5	6979
150	298.3	151.7	1966.2	6980
150	292.8	142.1	2060.7	6981
150	300.8	146.3	2056.7	6982
150	298.2	145.6	2048.0	6983
150	294.0	143.5	2049.3	6984
150	295.4	145.9	2024.4	6985
150	298.0	149.1	1998.7	6986
150	298.0	145.6	2047.3	6987
150	291.3	141.0	2065.6	6988
avg	**296.3**	**146.1**	**2028.7**	
stdev/%	**1.0 %**	**2.4 %**	**1.8 %**	

Figure A5: Without sphere gap - C4 3.2pu positive summary.

A.4 Impulse shapes of representative circuits

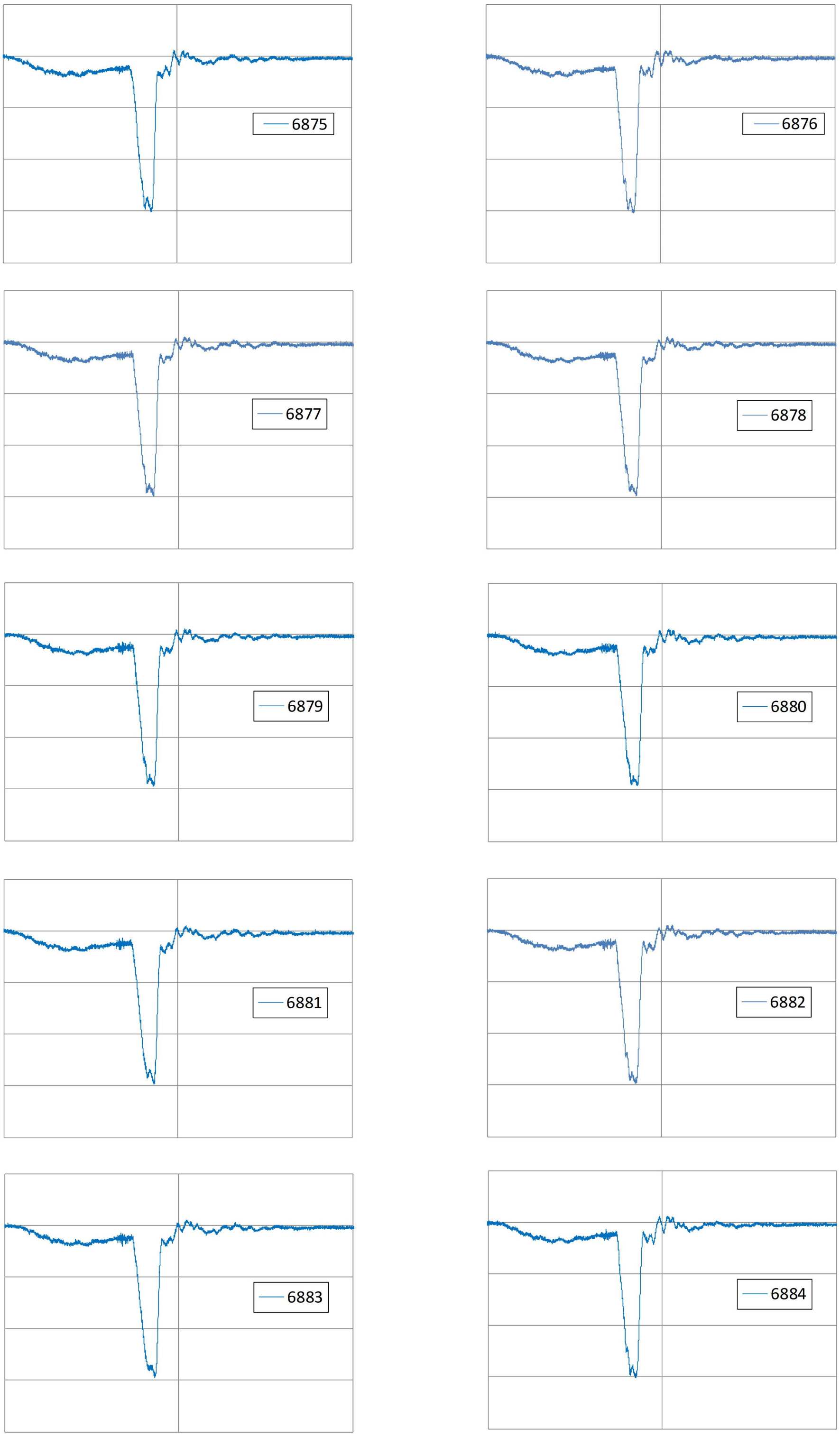

Figure A6: 10 successive impulses of B3 2.8pu negative case.

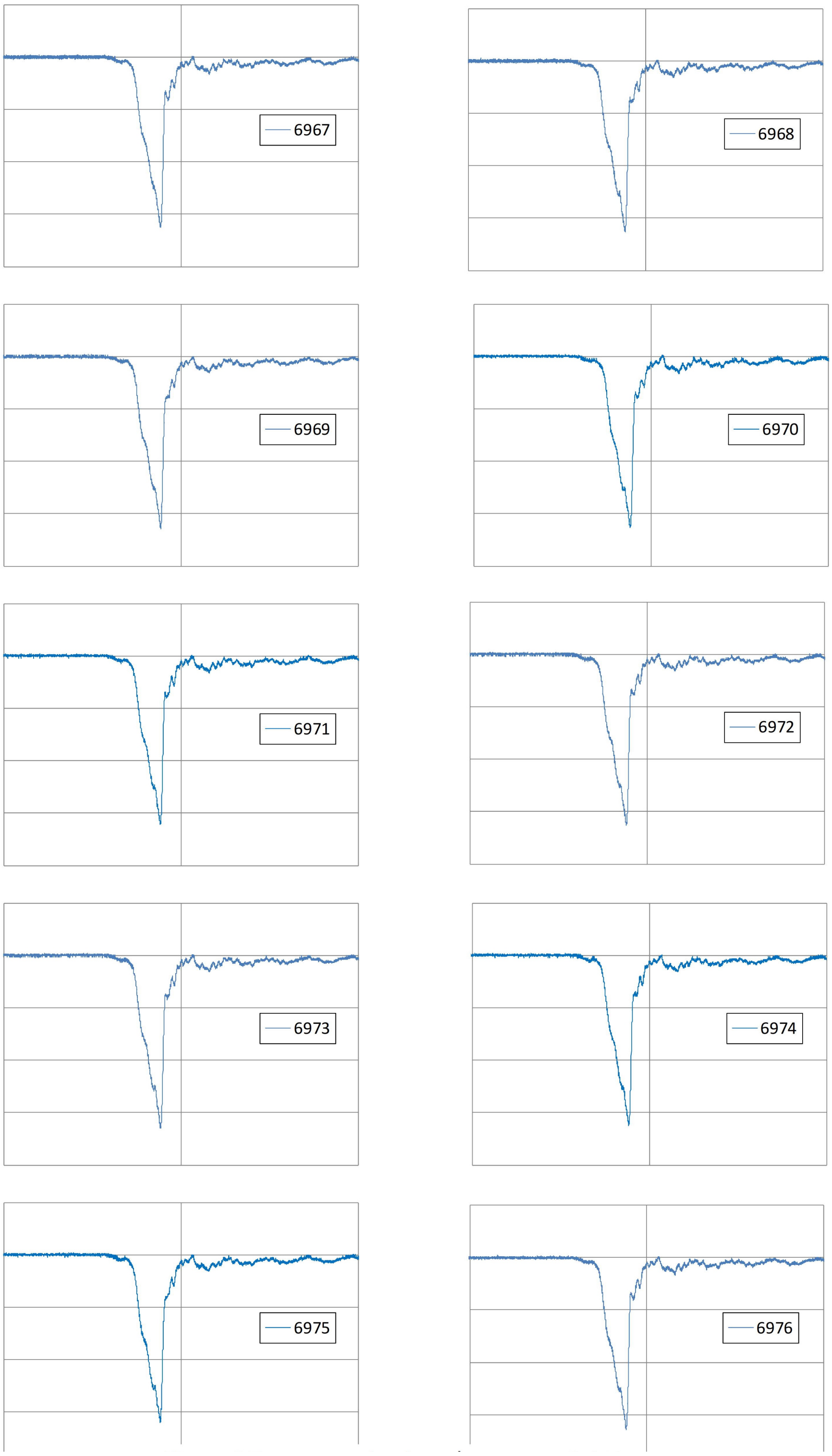

Figure A7: 10 successive impulses of C4 3.2pu positive case.

B Parts of proposed MVJ5000-N divider design

Dimensions are not shown here.

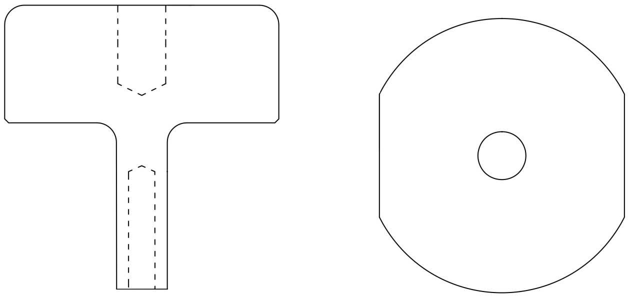

Figure B1: 1.

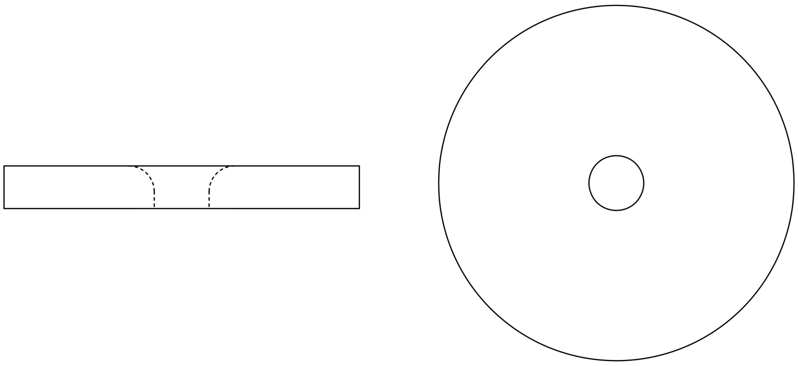

Figure B2: 2.

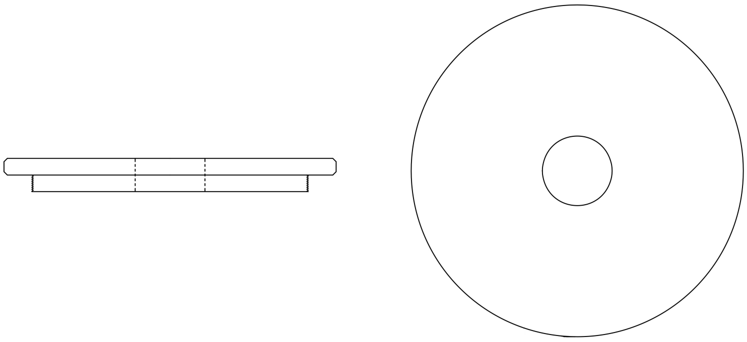

Figure B3: 3.

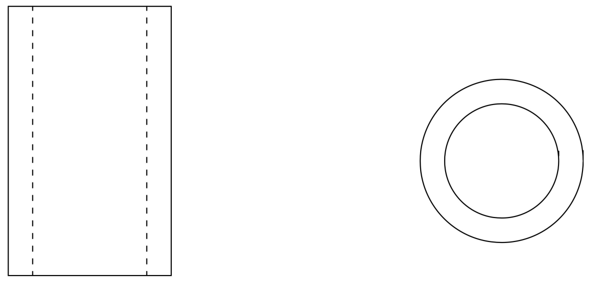

Figure B4: 4.

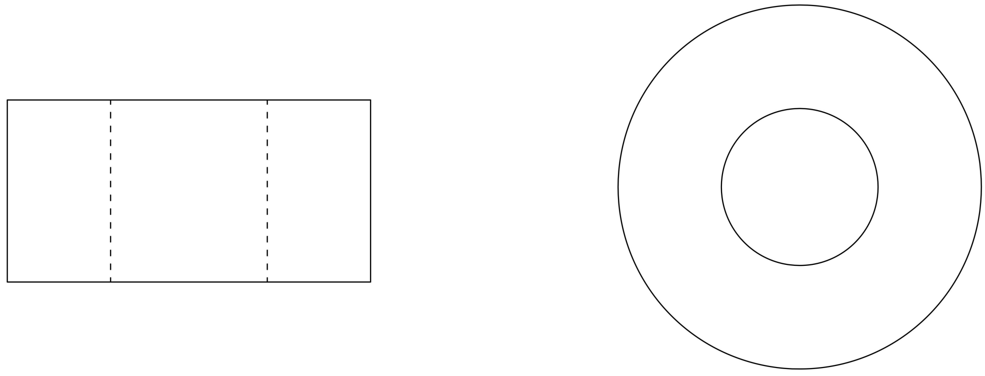

Figure B5: 5.

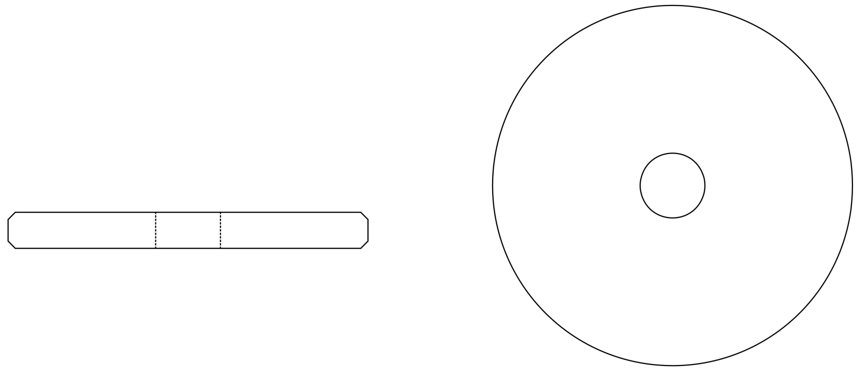

Figure B6: 6.

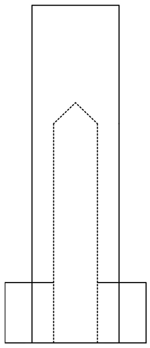

Figure B7: 8.

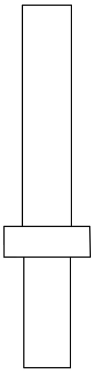

Figure B8: 9.

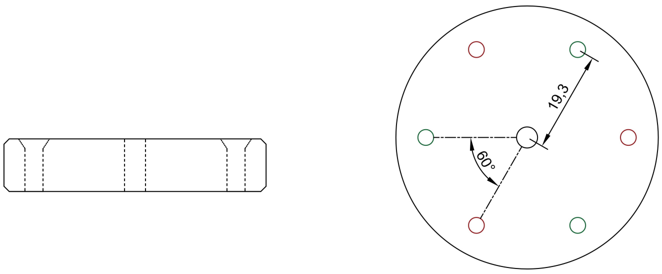

Figure B9: 10.

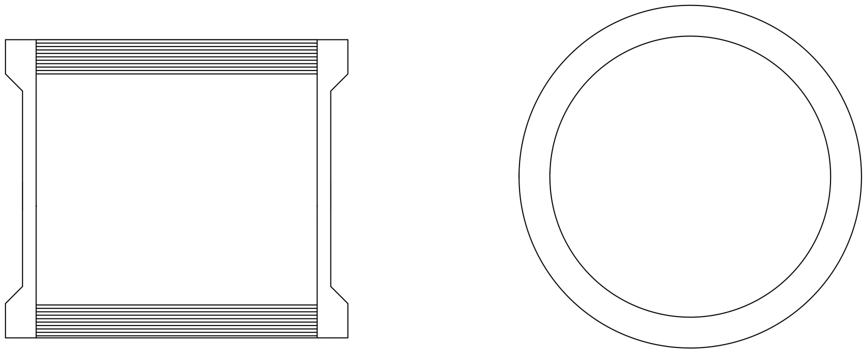

Figure B10: 12.

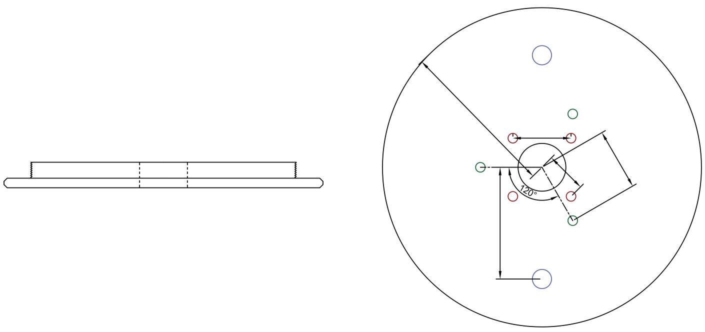

Figure B11: 13.

C Novel algorithm for linearly rising front chopped impulses

It was mentioned in literature review that steepness used to be the stress criterion (prior to advent of IEC-61211 [1]) to conduct impulse voltage puncture tests on insulators and to satisfy this criterion properly, linearly rising front chopped impulses were employed. But now IEC-61211 [1] doesn't specify any other criterion, except the peak value of test voltage, for the impulse front. This decreases the importance of the linearity of a front chopped impulse but still a code was written to study the linearity of the impulse front and to calculate the T_c from the measured impulses as per IEC-60060-1 [2]. This investigation could also provide deep understanding on reproducibility of puncture tests under various measurement circuit settings since very few labs all across the world perform puncture tests on insulators. A novel algorithm for evaluating the linearity of front chopped impulses, as per guidelines of IEC-60060-1 [2], is proposed here. The need to develop this algorithm was felt when the process to determine the linearity from software like MS Excel was not only hectic but also quite inaccurate. It must be noted that no such algorithm exists in literature so far. The algorithm also determines the T_c from the front chopped impulses using guidelines as per IEC-60060-1 [2]. Definition of linearity is given in Figure C5.

C.0.1 Mechanism of working

The algorithm is written in MATLAB since it is a great scripting application and the code can be modified quite easily for any future changes. The algorithm takes the text file, generated by the LeCroy WaveSurfer 24Xs for each individual impulse, as input. This file is later processed as per the flowchart shown in Figure C1. The flowchart of algorithm is pretty much self-explanatory. While IEC-60060-1 [2] only talks about an envelope of two lines parallel to AB (line through 30% and 90% points of the peak value), enclosing the impulse front from 30% of peak up-to the instant of chopping, but displaced from it by $\pm 5\%$ of T_1, the proposed algorithm makes the parallel lines of the envelope in such a way that they pass through the maximum deviated points from the line AB on both sides of the impulse front. This results in the maximum -/+ time deviations, which could help in tuning the measuring technique in a better way. The maximum -/+ time deviations could then be compared to the $\pm 5\%$ of T_1. If any of the -/+ deviations is more than the tolerance, the impulse will be termed as non-linear. The only anomaly is the fact that linearity is being checked between 30% of the peak value and the peak itself, instead of the Instant of Chopping (IOC). The reason for this is mentioned in the limitations of this algorithm. Also, the IOC and the T_c are determined.

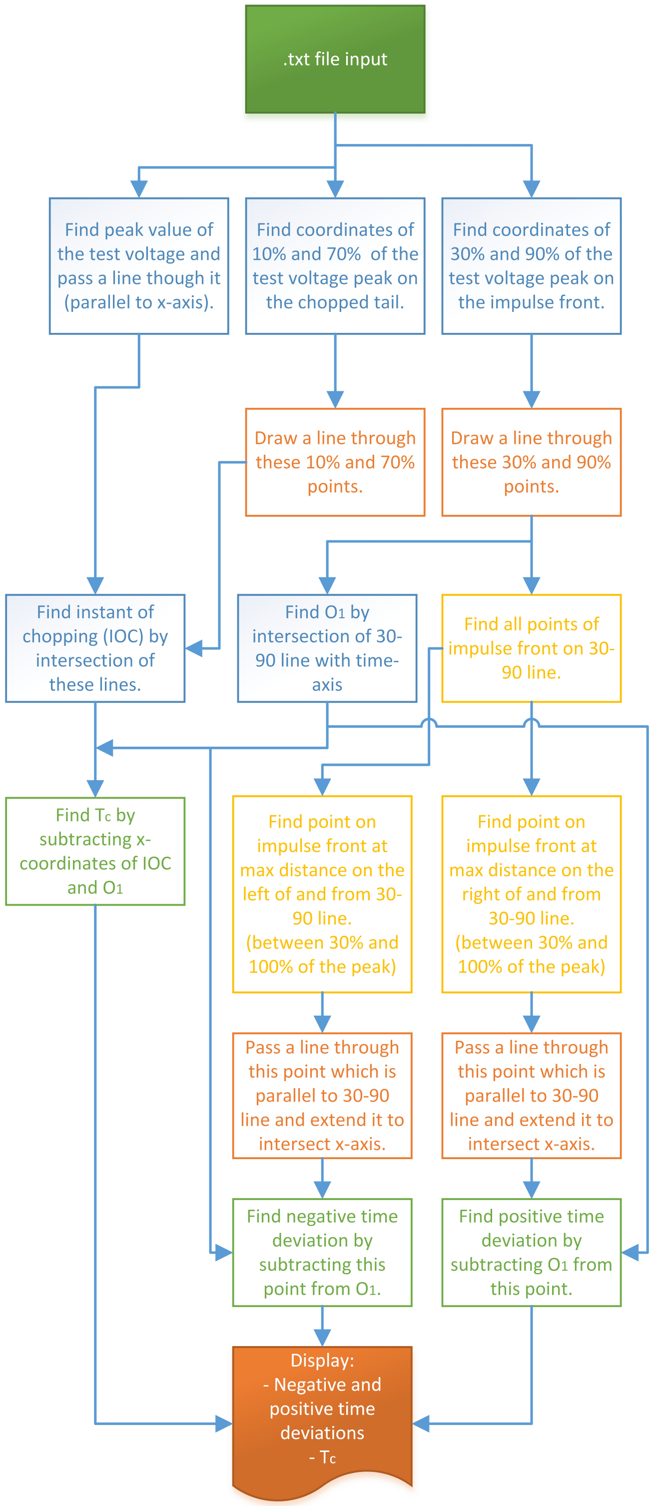

Figure C1: Flowchart for working of algorithm.

C.0.2 Comparison with results evaluated by MS Excel

Every time there is a need to determine the impulse linearity, it had to be done manually and visually in MS Excel, which obviously has a huge possibility of error. One impulse from C4 3.2pu negative case is shown as example in Figure C2.

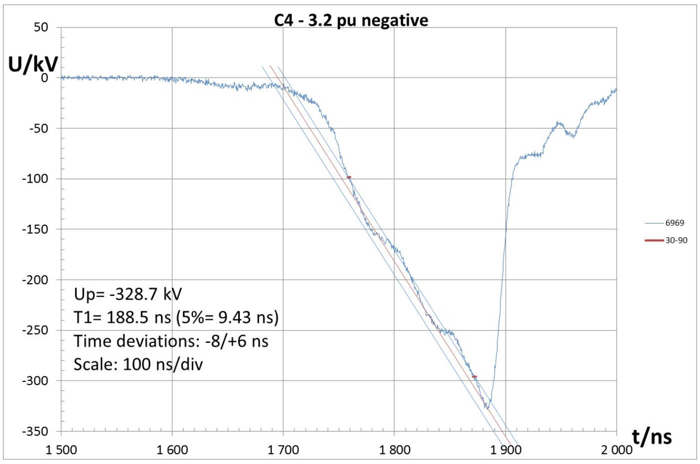

Figure C2: Manual linearity check of an impulse using MS Excel. Result: Linear.

The same impulse file run in the proposed algorithm is shown in Figure C3.

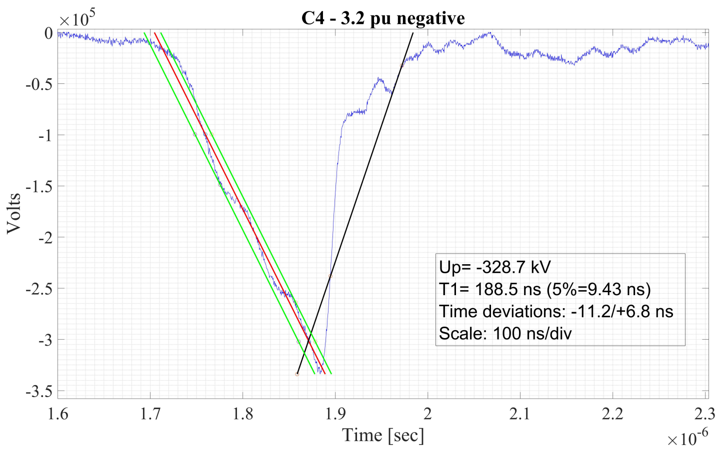

Figure C3: Automatic linearity check of the same impulse using proposed algorithm. Result: Non-linear.

If linearity evaluation is done by MS Excel then this impulse is linear, but the proposed algorithm clearly shows this impulse as non-linear because -/+ time deviations (-11.2/+6.8 ns) are more than the maximum tolerance value (±9.43ns). Therefore, this algorithm proves to be a very good tool for linearity evaluation of front chopped impulses. The black line in graph of algorithm is the 10-70 line and ends near the peak at IOC.

C.0.3 Features and limitations

This algorithm performs perfectly to a huge extent and has a great number of good features. However, it still has some limitations like every software that exists in this world. These features and limitations are discussed below:

C.0.3.1 Features

- The proposed algorithm has a very good noise rejection capability. It rejects noise to take points only on the impulse front/tail instead of the points on oscillations in the vicinity of 10%, 30%, 70% and 90% of the peak values.
- The algorithm is memory and speed optimised. The code compiles and builds in approximately 0.15 seconds while taking into account impulse text files with discrete time samples of the order of 10000 in number (sampling rate of 2.5 GS/s).
- The output also prints the T_c, calculated from the impulse using the guidelines from IEC-60060-1 [2].

C.0.3.2 Limitations

- The breakdown phenomenon in very fast front impulses is so rapid that even with 2.5 GS/s sampling rate, exact 10%, 30%, 70% and 90% of the peak values may never be acquired by the LeCroy WaveSurfer's data acquisition system. Hence, the algorithm only uses the approximate values as available in the impulse's input text file. This poses another error that affects the evaluation of the linearity. Interpolation between samples cannot be used because in MATLAB the input curve must be monotonic while here the impulse varies a lot between two consecutive samples at such a high sampling rate which makes it non-monotonic. Re-sampling within MATLAB was tried but it didn't give any better results either.
- The algorithm checks the linearity of the front chopped impulses between 30% of peak value and the peak itself, although it should have been the IOC. This is partly because of the reason as told above and partly because the impulses are so random in their behaviour that the IOC can even come way before the peak itself, as shown in Figure C3, contrary to the IOC that should come immediately after the peak as per IEC-60060-1 [2]. Therefore, the peak is the closest logical point that could be assumed as IOC with a fair amount of approximation. The Figure C4 shows the explanation of this point and the previous one.

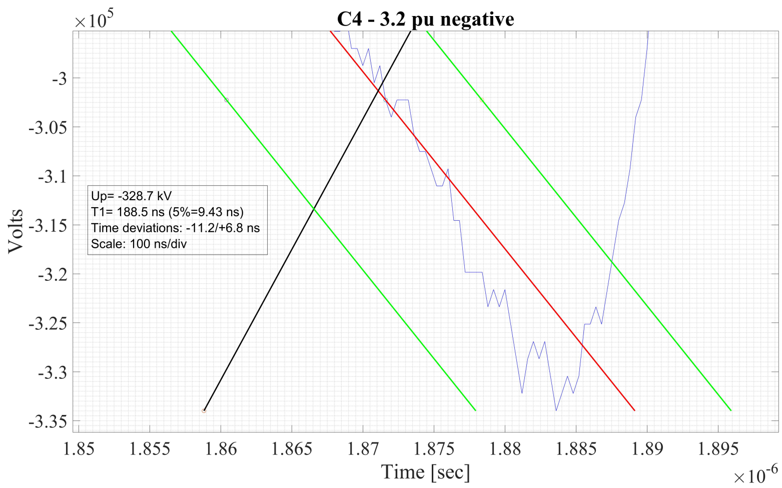

Figure C4: Variations between samples. The IOC is way behind the peak.

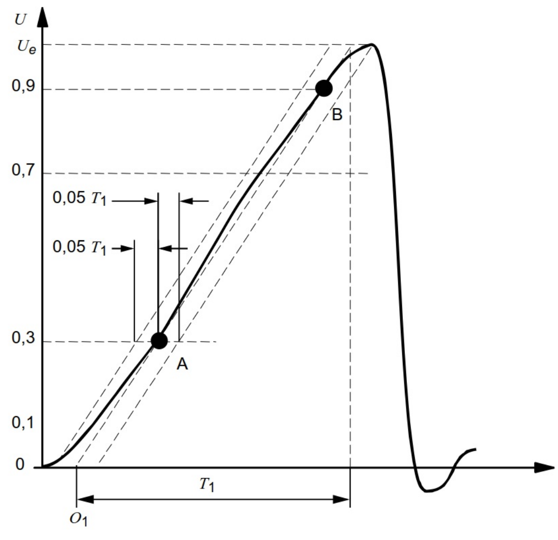

Figure C5: Definition of linearly rising front chopped impulse [2].